

(NASA-CR-132440) A NUMERICAL PROCEDURE  
FOR THE PARAMETRIC OPTIMIZATION OF THREE  
DIMENSIONAL SCRAMJET NOZZLES (Advanced  
Technology Labs., Inc., Westbury, N.Y.)  
84 p. HC \$7.25

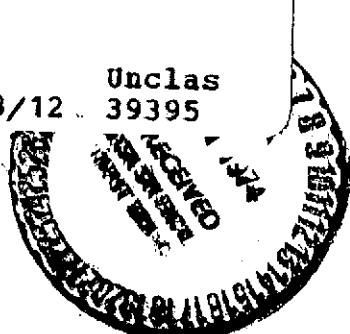


CSCL 20D

G3/12

N74-22926

Unclassified  
39395



ADVANCED TECHNOLOGY LABORATORIES, INC.

NASA CR-132440

N74 22926

OCTOBER 1973

ATL TR 188

A NUMERICAL PROCEDURE FOR THE PARAMETRIC  
OPTIMIZATION OF THREE DIMENSIONAL SCRAMJET NOZZLES

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INFORMATION SERVICE  
SPRINGFIELD, VA 22161

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I. INTRODUCTION

This report describes a numerical procedure permitting the rapid determination of the internal performance of a class of scramjet nozzle configurations. The geometric complexity of these configurations rules out attempts to employ conventional nozzle design procedures<sup>1</sup>, wherein properties at the nozzle exit plane are specified and wave cancellation techniques are then employed to design the wall surfaces. It is not feasible to stipulate exit conditions *a priori* and wave cancellation techniques employing three dimensional characteristics are beyond the current state of the art.

The approach developed is based on the construction of quasi two dimensional simple wave networks, wherein lateral expansion effects are incorporated via one dimensional approximations, as first suggested by Dr. Antonio Ferri<sup>2</sup>. A numerical procedure following this approach has been developed and results obtained are highly comparable to those obtained employing a characteristic procedure.

The numerical program developed permits the parametric variation of cowl length, turning angles on the cowl and vehicle undersurface and lateral expansion and is subject to fixed constraints such as the vehicle length and nozzle exit height. The program requires uniform initial conditions at the burner exit station and yields the location of all predominant wave zones, accounting for lateral expansion effects. In addition, the program yields the detailed pressure distribution on the cowl and vehicle undersurface and calculates the nozzle thrust, lift and pitching moment.

Due to the differing techniques required for the calculation of frozen flows as compared to equilibrium flows, two separate numerical programs have been developed. The first program analyzes constant  $\gamma$  frozen flow fields and a listing of this program is provided in Appendix II. The second program analyzes equilibrium hydrogen-air flow fields via equilibrium curve fits and its listing is provided in Appendix III. A complete program description is provided in Appendix I. The frozen flow program computes a complete nozzle flow field in

a fraction of a second while the equilibrium program has a running time of several seconds on a CDC 6600, as compared to running times of the order of a minute for a quasi two dimensional characteristic approach<sup>3</sup> and twenty minutes for a three dimensional numerical calculation<sup>4</sup>.

II. NUMERICAL PROCEDURES

Consider a typical nozzle configuration as depicted in Figure (1), where the lateral expansion distribution  $Z(x)$  may result from a combination of several nozzles merging into a single nozzle. It is assumed in this preliminary analysis that the jets after merging are bounded by sidewalls which extend downstream of the merged section. The initial flow (at the burner exit) is represented as an average uniform flow. The assessment of nonuniformities at the entrance station may be obtained applying the numerical procedures described in Reference (3).

For this configuration, the total amount of expansion from entrance conditions is known (based on two dimensional considerations) at the grid points labeled  $V_1$ ,  $C_1$ , A, B, C, D,  $V_3$ ,  $C_3$ ,  $E_2$ ,  $E_3$ , F and G and can be readily obtained at points  $V_2$ ,  $C_2$ ,  $E_1$  and  $E_4$ . The numerical procedure predicts the location of these grid points based on three dimensional flow considerations and effectively distributes the waves on the cowl and vehicle undersurface to assess the pressure distribution. It should be noted that a significant amount of the logical procedures in the numerical program are employed to distinguish the varying types of wave situations that may be encountered. In the configurations shown the expansion waves emanating from the cowl (at  $C_1$ ) and the vehicle (at  $V_1$ ) are both only partially captured on the undersurface and cowl respectively.  $\tau_v$  denotes the portion of the cowl expansion wave  $\Delta v_c$  captured on the vehicle undersurface while  $\tau_c$  denotes that portion of the vehicle expansion wave  $\Delta v_v$  captured on the cowl. In other situations, these waves may be totally captured or not captured at all, hence all these various situations must be distinguishable and treated discretely.

Before treating the overall logic entailed in a nozzle calculation, the calculational procedure for a typical grid point will be described:

A. Frozen Flow Grid Point Calculation - Consider the calculational procedure required to determine the location and properties of a point 3 (as shown in Figure 2) where properties at 1 and 2 are known and 1-3 and 2-3 are

characteristic surfaces. The total amount of expansion ( $\Delta v_3$ ) based on two dimensional considerations and the flow deflection ( $\theta_3$ ) is known at point 3. Along 1-3 or 2-3 we have

$$\frac{y_3 - y_{1,2}}{x_3 - x_{1,2}} = \frac{1}{2} [\tan(\theta_{1,2} \pm \mu_{1,2}) + \tan(\theta_3 \pm \mu_3)] \quad (1a,b)$$

Employing the two dimensional value of expansion  $\Delta v_3$  (from initial condition i) the Mach number  $M_3$  is obtained via the Prandtl-Meyer relation (where i denotes uniform initial flow properties at the burner exit)

$$\Delta v_3 = v_3 - v_i = \frac{\sqrt{\gamma+1}}{\gamma-1} \left( \tan^{-1} \sqrt{\frac{\gamma-1}{\gamma+1}} (M_3^2 - 1) - \tan^{-1} \sqrt{\frac{\gamma-1}{\gamma+1}} (M_i^2 - 1) \right) - \left( \tan^{-1} \sqrt{M_3^2 - 1} - \tan^{-1} \sqrt{M_i^2 - 1} \right) \quad (2)$$

employing an iterative procedure to solve this transcendental equation for  $M_3$ . Then, with the Mach angle determined

$$\mu_3 = \sin^{-1} \left( \frac{1}{M_3} \right) \quad (3)$$

Equations (1a) and (1b) yield a tentative location for point 3, and the area ratio  $(A/A^*)_3$  is calculated based on two dimensional considerations

$$\left( \frac{A}{A^*} \right)_3 = \frac{M_3 \left( 1 + \frac{\gamma-1}{2} M_3^2 \right)^{\frac{\gamma+1}{2(\gamma-1)}}}{\left( \frac{\gamma+1}{2} \right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad (4)$$

This ratio is corrected for lateral expansion by multiplying it by the ratio  $Z_3/Z_i$  where the lateral expansion variable is expressed by a suitable polynomial curve fit

$$Z(x) = Ax^2 + Bx + C \quad (5)$$

where  $Z_3 = Z(x_3)$  and  $Z_i$  denotes the lateral extent of the nozzle at the initial station.

$$\left(\frac{A}{A^*}\right)_3 = \left(\frac{A}{A^*}\right)_3 * Z_3/Z_i \quad (6)$$

Then, the three dimensional corrected Mach number is obtained by replacing the two dimensional area ratio in Equation (4) by the three dimensional value given by Equation (6), and solving Equation (4) for  $M_{3,3D}$  by an iterative process. Equations (1a) and (1b) are resolved using the corrected Mach angle  $\mu_{3,3D}$  and the entire procedure is repeated until two successive values of  $x_3$  are within a prescribed tolerance.

A similar procedure is used to determine properties at grid points on boundaries with Equation (1a) or (1b) replaced with an equation describing the body geometry. Desired variables (P, T etc.) are then simply obtained by isentropic, constant  $\gamma$  expansions from initial conditions.

B. Equilibrium Flow Grid Point Calculation - The geometric location of point 3 is obtained employing Equations (1a) and (1b) just as for the frozen calculation. The known two dimensional value of expansion  $\Delta v_3$  is subdivided into a series of small  $\Delta v_j$  increments. The initial value of isentropic exponent  $\Gamma$  is obtained from

$$\Gamma = \Gamma (P, \phi, h) \quad (7)$$

where Equation (7) has been curve fit for equilibrium hydrogen-air as described in Reference (5).

The characteristic compatibility relation

$$\frac{d \ln P}{\Gamma} \pm \frac{dv}{\sin \mu \cos \mu} = 0 \quad (8)$$

applied across the interval  $\Delta v_j$  yields the pressure, holding  $\Gamma$  and  $\mu$  equal to their values at the start of the increment. The density is obtained from the isentropic pressure-density relation

$$P/\rho^{\Gamma} = \text{constant} \quad (9)$$

The velocity is obtained from the Bernoulli relation;

$$\frac{dP}{\rho} + \frac{1}{2} dV^2 = 0 \quad (10)$$

the enthalpy from the constancy of stagnation enthalpy;

$$h + \frac{1}{2} V^2 = H = \text{constant} \quad (11)$$

and the Mach number from;

$$M = V/a; \quad a = \left(\frac{P}{\rho}\right)^{\frac{1}{2}} \quad (12)$$

where  $\Gamma$  has been reevaluated employing Equation (7). This procedure is repeated in small steps  $\Delta v_j$  until the full wave  $\Delta v_3$  has been integrated. Having the two dimensional value of  $M_3$ , point 3 can be tentatively located employing Equations (1a) and (1b). Then, the two dimensional area ratio can be computed from mass flow considerations

$$\left(\frac{A_3}{A_i}\right)_{2D} = \rho_i V_i / \rho_3 V_3 \quad (13)$$

Since the effective area based on three dimensional considerations is

$$\left(\frac{A_3}{A_i}\right)_{3D} = \left(\frac{A_3}{A_i}\right)_{2D} * Z_3/Z_i \quad (14)$$

the product  $\rho_3 V_3$  must be divided by  $Z_3/Z_i$  to conserve mass flow

$$\left(\rho_3 V_3\right)_{3D} = \left(\rho_3 V_3\right)_{2D} * \frac{Z_i}{Z_3} \quad (15)$$

Then an iteration procedure is performed to determine the value of three dimensional expansion  $(\Delta v_3)_{3D}$ , the correct value being that which yields  $(\rho_3 V_3)_{3D}$  after application of the integration procedure of Equations (7) thru (12), and an update of the location of point 3 using Equations (1a) and (1b).

### III. DETERMINATION OF NOZZLE FLOW FIELDS

A nozzle calculation is performed subject to the following constraints:

1. The initial profile is uniform. For the frozen flow (constant  $\gamma$ ) calculation this requires specification of the pressure  $P_i$ , flow deflection angle  $\theta_i$ , Mach number  $M_i$ , and specific heat ratio  $\gamma$ . For the equilibrium calculation one must specify  $P_i$ ,  $\theta_i$ ,  $M_i$ , the temperature  $T_i$  and the fuel-air equivalence ratio  $\phi_i$ .
2. The initial turning at the vehicle undersurface ( $\Delta v_v$ ) and cowl ( $\Delta v_c$ ) occur via sharp corners as depicted in Figure (1).
3. The wall segments downstream of these sharp corners remain straight until the expansion waves emanating from the cowl and vehicle undersurface reach the walls (points  $V_3$  and  $C_3$  of Figure 1).
4. The nozzle exit height is specified ( $y_{v_2} - y_{c_2}$ ).
5. The recompression on the vehicle undersurface (between  $V_3$  and  $V_2$ ) is parabolic while the cowl between  $C_3$  and  $C_2$  is straight.
6. The lateral expansion  $Z(x)$  is specified via a geometric curve fit.
7. The cowl length and vehicle length are specified.

The numerical logic employed in the parametric design procedure is to treat the cowl length ( $x_{c_2} - x_{c_1}$ ) and the vehicle undersurface expansion  $\Delta v_v$  as parametric variables for fixed values of cowl turning  $\Delta v_c$ , nozzle exit height, lateral expansion and vehicle length. Initially, a short cowl length should be

chosen such that the expansion waves from the vehicle expansion fan miss the cowl. For this cowl length, the value of the vehicle undersurface expansion wave is varied in small increments, the minimum amount of turning being that which introduces no recompression in the region  $V_3$  to  $V_2$  (i.e., the undersurface is flat) to a value for which the recompression produces zero deflection at the end of the vehicle. This is illustrated in Figure (3). Then the cowl length is increased in specified increments and the entire procedure is repeated.

For a given nozzle configuration, the calculational procedure is as follows:

1. Grid points A, B, C and D are calculated following the procedure described in the previous section. The two dimensional values of expansion from initial conditions and flow deflection angles at these points are:

$$\Delta v_A = 0, \quad \theta_A = \theta_i$$

$$\Delta v_B = \Delta v_C, \quad \theta_B = \theta_i - \Delta v_C$$

$$\Delta v_C = \Delta v_V, \quad \theta_C = \theta_i + \Delta v_V$$

$$\Delta v_D = \Delta v_C + \Delta v_{V_1}, \quad \theta_D = \theta_i + \Delta v_V - \Delta v_C$$

2. The amount of the vehicle expansion wave captured on the cowl ( $\tau_c$ ) is determined by an iterative procedure. A value of  $\tau_c$  is assumed which yields the location of grid points T and W as depicted in Figure (1). The correct value of  $\tau_c$  is that for which the wave from W intersects the end of the cowl precisely. A linear error extrapolation routine is used to speed convergence of this iterative process. Having determined  $\tau_c$ , the two dimensional expansion at the end of the cowl (assuming no recompressions between  $C_3$  and  $C_2$ ) is

$$\Delta v_{c_2} = \Delta v_c + 2\tau_c$$

since the portion of the wave captured is fully reflected.

3. The amount of the cowl expansion wave captured on the vehicle undersurface  $\tau_v$  is determined by a similar iterative procedure and the two dimensional expansion at the end of the vehicle is given by

$$\Delta v_{v_2} = \Delta v_v + 2\tau_v + \Delta v_r$$

where the recompression  $\Delta v_r$  is given by

$$\Delta v_r = \theta_{v_2} - \theta_{v_3}$$

Note that for given nozzle parameters, the equation for the parabolic recompression between  $v_3$  and  $v_2$  is determined in the course of the numerical calculations. Specification of the cowl length and expansion  $\Delta v_c$  yields  $x_{c_2}$  and  $y_{c_2}$ ; the nozzle length and exit height yields  $x_{v_2}$  and  $y_{v_2}$  and the vehicle turn  $\Delta v_v$  yields  $x_{v_3}$  and  $y_{v_3}$ . Hence, the parabola is determined for each case satisfying the conditions

$y_{v_3}$  and  $\theta_{v_3}$  specified at  $x_3$

$y_{v_2}$  specified at  $x_2$

(where  $\theta_{v_3} = \theta_1 + \Delta v_v$ ).

4. The determination of the exit profile ( $E_0-E_5$ ) is highly dependent on the particular configuration being studied. For the case depicted in Figure (1), the cowl and vehicle expansion waves are partially captured resulting in a zone of uniform two dimensional wave strength between  $E_2$  and  $E_3$  ( $\Delta v_{E_2} = \Delta v_{E_3} = \Delta v_v + \Delta v_c$ ). Points

$E_1$  and  $E_4$  have this value of expansion and additionally receive portions of the reflected waves. Hence, the two dimensional value of expansion experienced at  $E_1$  is given by

$$\Delta v_{E_1} = \Delta v_{v_1} + \Delta v_{c_1} + f^* \tau_c$$

where  $f = 1 - \frac{(y_{E_1} - y_{c_2})}{(y_{E_2} - y_{c_2})}$

while that at  $E_4$  is given by

$$\Delta v_{E_4} = \Delta v_{v_1} + \Delta v_{c_1} + g^* (\tau_v + \Delta v_r)$$

where  $g = 1 - \frac{(y_{E_4} - y_{v_2})}{(y_{E_3} - y_{v_2})}$

The corresponding flow deflection angles are:

$$\theta_{E_1} = \theta_i + \Delta v_{v_1} - \Delta v_{c_1} - f^* \tau_c$$

$$\theta_{E_4} = \theta_i + \Delta v_{v_1} - \Delta v_{c_1} + g^* (\tau_v + \Delta v_r)$$

Now consider the wave configuration depicted in Figure (4) (where the F point and G point are downstream of the exit plane and hence not required in the calculational procedure). In this situation, the two dimensional value of expansion experienced at  $E_1$  is given by

$$\Delta v_{E_1} = \Delta v_{c_1} + \tau_c + f_1^* (\Delta v_{v_1} - \tau_c)$$

where  $f_1 = \frac{y_{E_1} - y_{c_2}}{y_{E_2} - y_{c_2}}$

while that at  $E_4$  is given by

$$\Delta v_{E_4} = \Delta v_{V_1} + \tau_v + g_1 * (\Delta v_{C_1} - \tau_v)$$

where  $g_1 = \frac{y_{E_4} - y_{V_2}}{y_{E_3} - y_{V_2}}$

The corresponding flow deflection angles are:

$$\theta_{E_1} = \theta_i - \Delta v_{C_1} + \tau_c + f_1 * (\Delta v_v - \tau_c)$$

$$\theta_{E_4} = \theta_i + \Delta v_{V_1} - \tau_v - g_1 * (\Delta v_c - \tau_v).$$

The program developed analyzes both these wave configurations and combinations of the two. In addition, it can analyze cases where the full cowl expansion is captured on the vehicle undersurface as depicted in Figure (5), and cases where no region of uniform two dimensional wave strength on the exit plane exists as depicted in Figure (6). For these latter cases, not all points at the exit plane are computed by the program due to the logical complexities imposed by the wide variety of wave configurations that may occur.

IV. DETERMINATION OF THRUST, LIFT AND PITCHING MOMENT

The thrust, lift and pitching moment are determined by a combination of integrating the pressure distribution on the cowl and vehicle undersurface and by a momentum flux calculation. Referring to Figure (1), the pressure distribution on the vehicle undersurface between  $V_1$  and  $V_3$  and on the cowl between  $C_1$  and  $C_3$  are readily determined since the two dimensional values of expansion on these surfaces are constant ( $\Delta v_{V_1}$  and  $\Delta v_{C_1}$  respectively). Then, the pressure is determined by accounting for lateral expansion by the procedure described in Section II (i.e., by employing Equations (1) - (6) for frozen flows and Equations (7) - (15) for equilibrium flows with the value of two dimensional expansion being constant on each surface).

Since the lift and pitching moment are quite sensitive to the pressure distribution the expansion fans from the cowl and undersurface must be distributed properly in the region  $V_3$  to  $V_2$  on the undersurface and  $C_3$  to  $C_2$  on the cowl. For points on the vehicle undersurface (as depicted in Figure 7) the value of two dimensional expansion at a point  $x^*$  is given by

$$\Delta v^* = \Delta v_{V_1} + \Delta v_{V_2}^* + 2\tau^*$$

where

$$\Delta v_{V_2}^* = \theta^* - \theta_{V_3}$$

and

$$\tau^* = \tan^{-1} \left( \left[ \frac{(x_{V_3} - x_{C_1})}{(x_{V_2}^* - x_{C_1})} - 1 \right] / \left[ \frac{(x_{V_3} - x_{C_1})}{(x_{V_2} - x_{C_1})} - 1 \right] * \tan(\tau_V) \right) \quad (16)$$

In the above relation  $\tau^*$  varies from 0 to  $\tau_V$  over the interval  $x_{V_3}$  to  $x_{V_2}$ . If the full wave is captured on the undersurface as depicted in Figure (5), then  $\tau^*$  would vary from 0 to  $\tau_V$  in the interval  $x_{V_3}^*$  to  $x_{V_4}^*$  which is affected in Equation (16) by replacing  $x_{V_2}$  by  $x_{V_4}$ . Then  $\tau^* = \tau_V$  between  $x_{V_4}^*$  and  $x_{V_2}$ .

Similarly, for points on the cowl (Figure 8) the value of two dimensional expansion at a point  $\tilde{x}$  is given by

$$\Delta \tilde{v} = \Delta v_c + 2\tilde{\tau}$$

where

$$\tilde{\tau} = \tan^{-1} \left( \frac{\left[ \frac{(x_{c_3} - x_{v_1})}{(\tilde{x} - x_{v_1})} - 1 \right] / \left[ \frac{(x_{c_3} - x_{v_1})}{(x_{c_2} - x_{v_1})} - 1 \right] * \tan(\tau_c)}{\left[ \frac{(x_{c_3} - x_{v_1})}{(x_{c_2} - x_{v_1})} - 1 \right] * \tan(\tau_c)} \right) \quad (17)$$

In this relation  $\tilde{\tau}$  varies from 0 to  $\tau_c$  in the interval  $x_{c_3}$  to  $x_{c_2}$ . Knowing the two dimensional values of expansion, the pressure distribution accounting for lateral effects is obtained as previously described.

The lift is determined solely from the pressure distribution on the cowl and vehicle undersurface assuming that the internal walls and side flow fences provide no contribution. Then, the lift is given by the integration

$$L = \int_{x_{v_1}}^{x_{v_2}} (P - P_\infty) Z(x) dx - \int_{x_{c_1}}^{x_{c_2}} (P - P_\infty) Z(x) dx \quad (18)$$

The values of thrust and pitching moment contributed by the cowl and vehicle undersurface are given by

$$Th^* = \int_{y_{v_1}}^{y_{v_2}} (P - P_\infty) Z dy - \int_{y_{c_1}}^{y_{c_2}} (P - P_\infty) Z dy \quad (19)$$

$$M^* = - \int_{y_{v_1}}^{y_{v_2}} (P - P_\infty) Z (y - \bar{y}) dy + \int_{x_{v_1}}^{x_{v_2}} (P - P_\infty) Z (x - \bar{x}) dx \quad (20)$$

$$+ \int_{y_{c_1}}^{y_{c_2}} (P - P_\infty) Z (y - \bar{y}) dy - \int_{x_{v_1}}^{x_{v_2}} (P - P_\infty) Z (x - \bar{x}) dx$$

where  $(\bar{x}, \bar{y})$  is the origin for the pitching moment.

To assess the sidewall contributions to the thrust and pitching moment, momentum conservation integrals must be applied at the entrance and exit planes of the nozzle since the sidewall pressures are not explicitly calculated in the analysis. Before calculating these integrals, the exiting and entering mass flux must be compared since slight discrepancies in mass flow can yield substantial errors in momentum integrals. The mass flux is given by

$$\psi = \int_y \frac{\rho v \sin(\theta_s - \theta)}{\sin \theta_s} Z dy \quad (21)$$

where  $\theta_s$  represents the inclination of the plane of integration with respect to the horizontal (i.e., for the exit plane depicted in Figure 1,  $\theta_s = \tan^{-1} ((y_{v_2} - y_{c_2}) / (x_{v_2} - x_{c_2}))$ ). To perform an integration over the exit plane where properties are only known at the discrete points  $E_0 - E_5$ , the two dimensional value of wave strength is linearly distributed between  $E$  points and properties are obtained at these interpolated points following the procedures outlined in Section II. The properties are corrected to yield the correct existing mass flow as follows for frozen flow.

Let  $R = \psi_2 / \psi_1$  represent the ratio of exiting to entering mass flux as determined by the integration of Equation (21). For frozen flows, the mass flux can be expressed solely in terms of the Mach number distribution

$$\psi = \int_y \frac{D(M) \sin(\theta_s - \theta)}{\sin \theta_s} Z dy \quad (22)$$

where

$$D(M) = M \left( 1 + \frac{\gamma-1}{2} M^2 \right)^{-(\gamma+1)/2(\gamma-1)} \quad (23)$$

Then, at all points on the exit profile  $D(M)$  is corrected by division by  $R$

$$D'(M) = D(M)/R$$

and the corrected Mach number is found by solving the transcendental equation (Equation 23) for  $M'$  by an iterative procedure; then, desired properties are obtained by standard isentropic expansions

$$P' = P \left( \frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M'^2} \right)^{\frac{\gamma}{\gamma-1}} \quad (24)$$

$$T' = T \left( \frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M'^2} \right) \quad (25)$$

For equilibrium calculations, at all points on the exit plane, the product  $(\rho u)$  is divided by  $R$

$$(\rho u)' = \frac{\rho u}{R}$$

and the value of  $\Delta v'$  is sought that produces this change. Hence, an iterative procedure is employed wherein the value of  $\Delta v$  at all points on the exit plane is perturbed to produce the corrected product  $(\rho u)'$  employing Equations (7) - (12).

Then, having corrected the mass flow by modification of properties at the exit plane, the momentum flux is given by

$$F_x = \int_y \left[ \frac{\rho V^2 \sin(\theta_s - \theta) \cos \theta + (P - P_\infty) \sin \theta_s}{\sin \theta_s} \right] z dy \quad (26)$$

which for frozen flow, simplifies to

$$F_x = \int_y \left[ \frac{\gamma P M^2 \sin(\theta_s - \theta) \cos \theta + (P - P_\infty) \sin \theta_s}{\sin \theta_s} \right] z dy \quad (27)$$

Then, the total thrust is given by

$$Th = F_{x_2} - F_{x_1} \quad (28)$$

where 1 and 2 represent integrations over the entrance and exit stations respectively. The thrust attributed to the sidewalls is then given by

$$Th_{sw} = Th - Th^* \quad (29)$$

The pitching moment is given by

$$M = PM_2 - PM_1 \quad (30)$$

where

$$PM = \int_y [f_x(y-\bar{y}) - f_y(x-\bar{x})] z dy \quad (31)$$

and

$$f_x = \frac{\rho V^2 \sin(\theta_s - \theta) \cos \theta + (P - P_\infty) \sin \theta_s}{\sin \theta_s} \quad (32)$$

$$f_y = \frac{\rho V^2 \sin(\theta_s - \theta) \sin \theta + (P - P_\infty) \cos \theta_s}{\sin \theta_s} \quad (33)$$

V. SAMPLE CALCULATIONS

To assess the validity of the developed program, a comparison was made with the source flow characteristic program described in Reference (3). The nozzle configuration and resultant wave field (as determined from the parametric design program (NOZD)) is depicted in Figure (9). The data at various points in the flow field is given in Table I. A comparison of the pressure distributions downstream of the cowl and undersurface expansion fans is depicted in Figure (10). The source flow characteristic program (NOZBOD) had the source located at  $x = -20$  and had the sharp turns at the cowl and undersurface occur over a distance  $\Delta x = .15$ . The source flow program calculates frozen chemistry via appropriate curve fits while the wave program calculates constant  $\gamma$  frozen flows. It should be noted that the program NOZD required .4 seconds for this calculation as compared with 55 seconds for NOZBOD, indicating that the ratio of running times for frozen flow calculations is of the order of 140 to 1. The pressure distribution as calculated by NOZD shows excellent agreement with the second order source flow calculations of NOZBOD and the thrust values as calculated by the two programs agreed to within one percent. Additionally, depicted in Figure (10) are the corresponding pressure distributions on the cowl and undersurface for the equivalent nozzle with no lateral expansion. The data at various points in the flow field for this calculation are given in Table II.

To illustrate the parametric design process, a two dimensional calculation was performed for a nozzle subject to the following constraints:

Entrance Height	1.0
Exit Height	6.0
Vehicle Length	15.0
Cowl Expansion	$10^{\circ}$

For these constraints, the cowl length was systematically varied from 3 to 9 and for each cowl length the vehicle undersurface expansion was varied in one degree increments as depicted in Figure (3).

The initial conditions for this case are:

$$P = 850 \text{ lb/ft}^2$$

$$M = 3$$

$$\gamma = 1.4$$

$$\Phi = 0$$

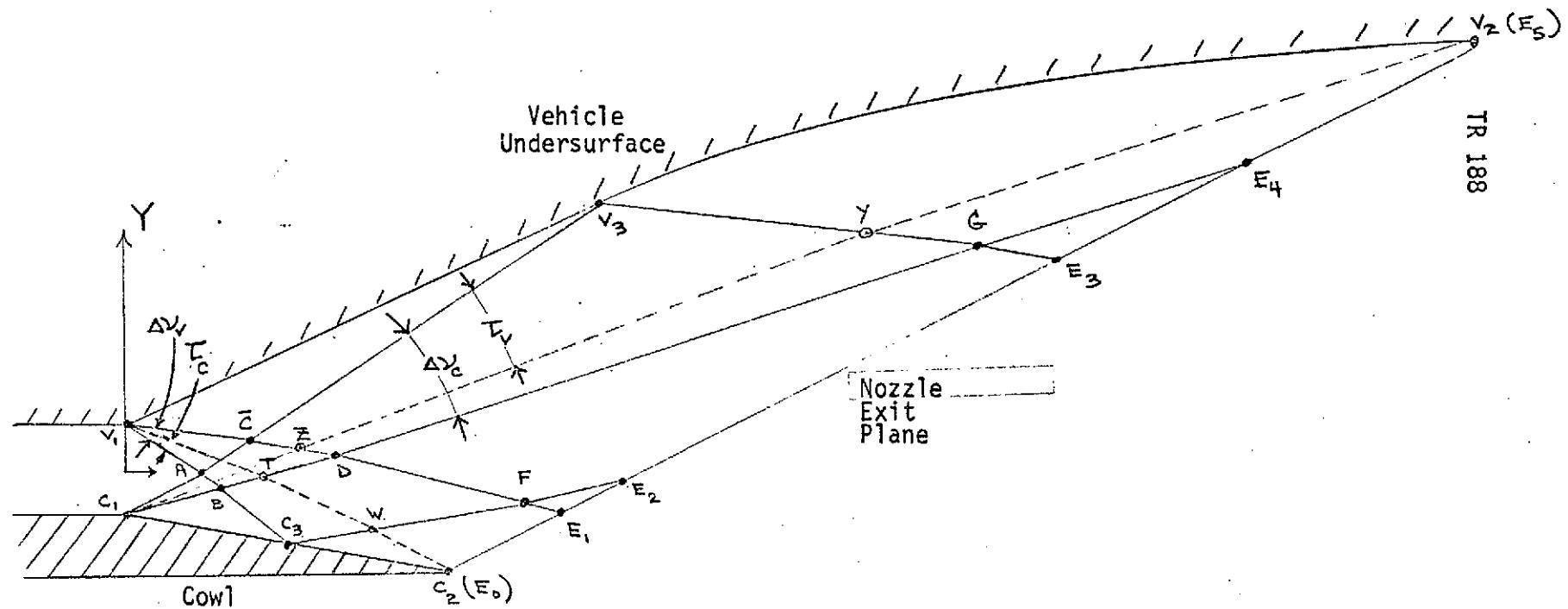
and  $P_\infty = 23.1 \text{ lb/ft}^2$

The thrust is plotted versus vehicle turning angle with the cowl length as a parameter in Figure (11), and the lift is plotted in Figure (12).

## VI.

CONCLUSIONS

The numerical program developed should be a useful tool in rapidly assessing the affects of varying dominant parameters on scramjet exhaust nozzles. The results obtained by this program compare favorably with more precise analytical methods with a considerable savings in overall running time. While the current program cannot analyze all possible configurations, it is felt that once a user gains familiarity with the program, changes to accommodate other configurations can readily be made.



\*[Note that  $\Delta v$  is the wave strength of an expansion fan, not the geometric angle between initial and final rays.]

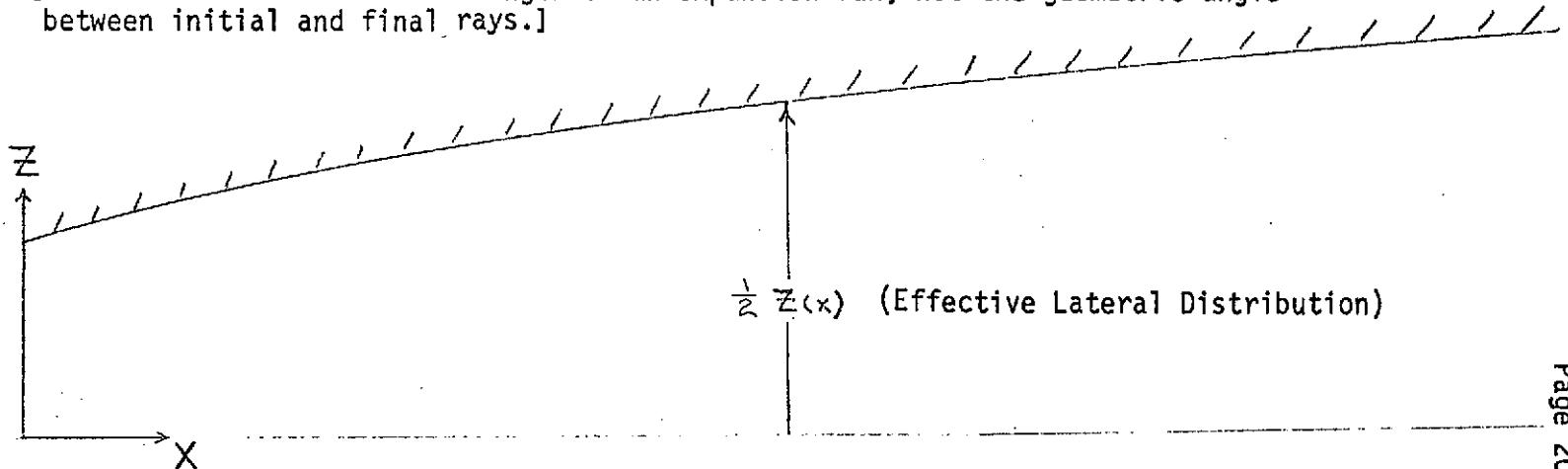


FIGURE 1. TYPICAL NOZZLE CONFIGURATION

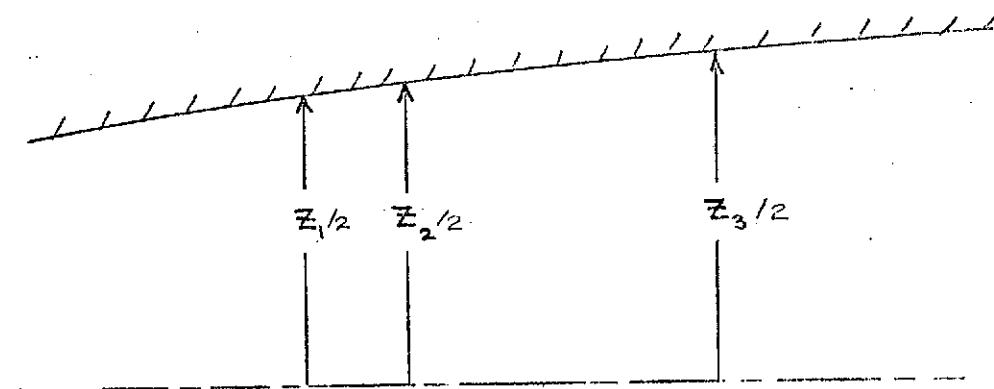
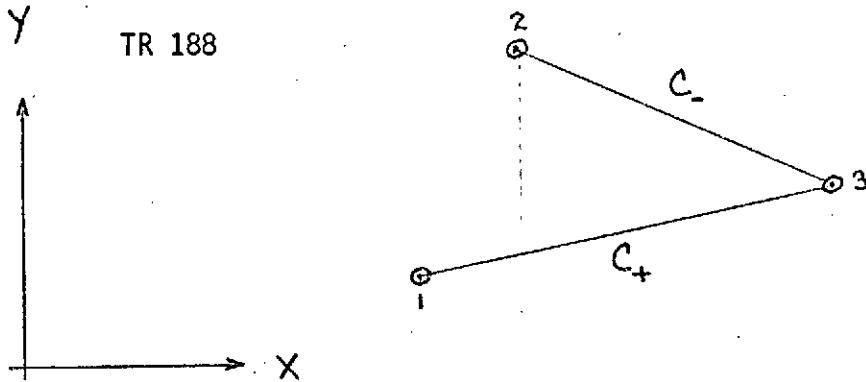


FIGURE 2. GRID POINT CALCULATION

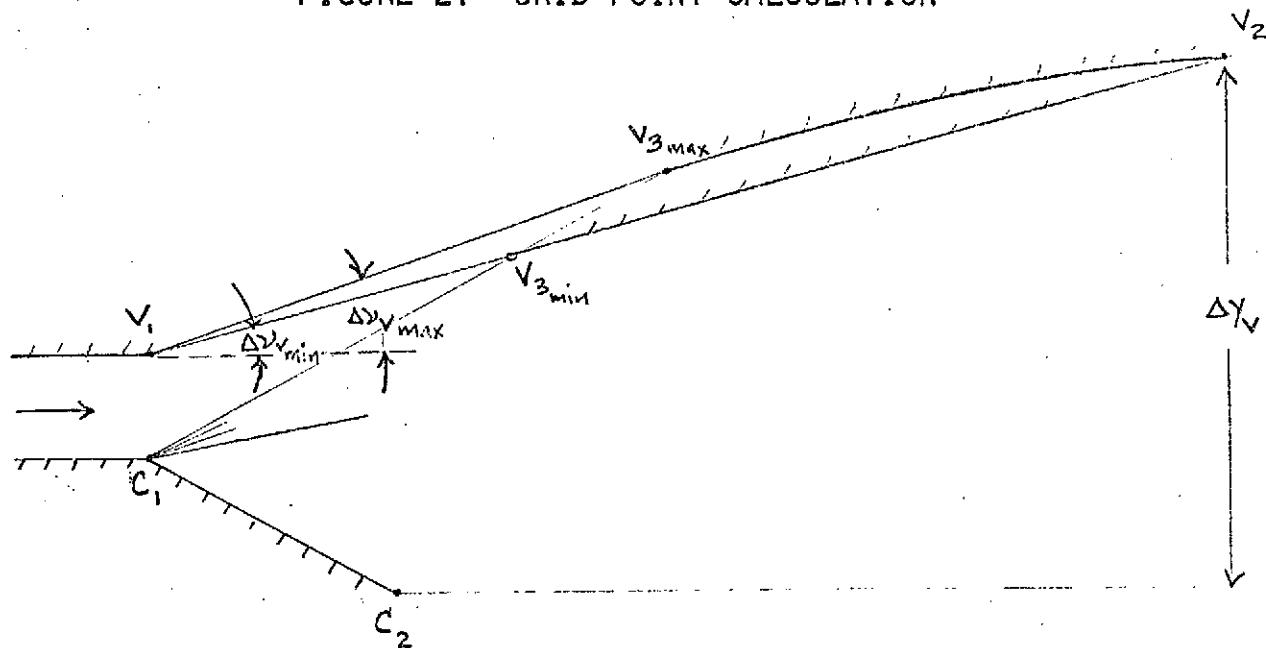


FIGURE 3. VARIATION OF VEHICLE EXPANSION WAVE STRENGTH

TR 188

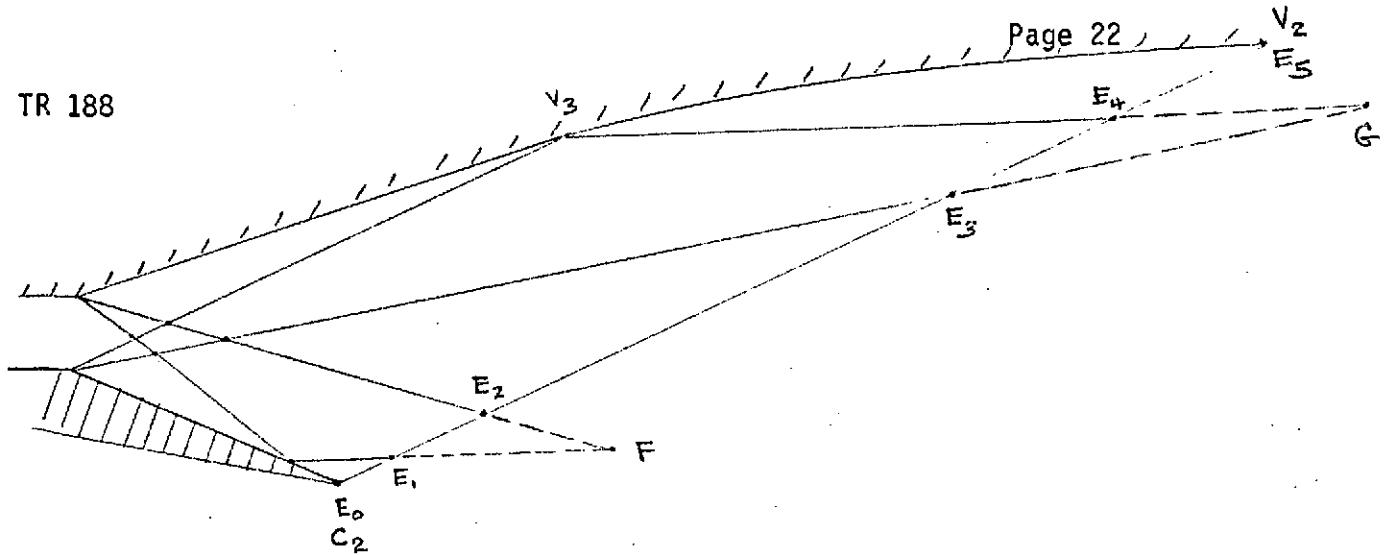


FIGURE 4. F AND G POINT DOWNSTREAM OF EXIT PLANE

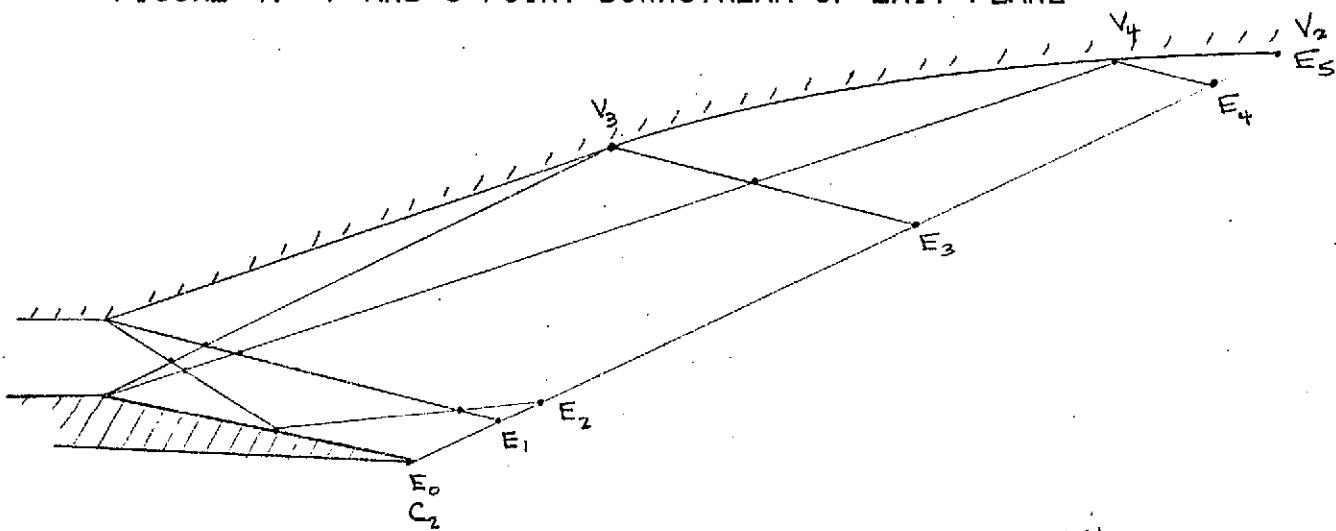


FIGURE 5. FULL COWL WAVE CAPTURED  
ON UNDERSURFACE

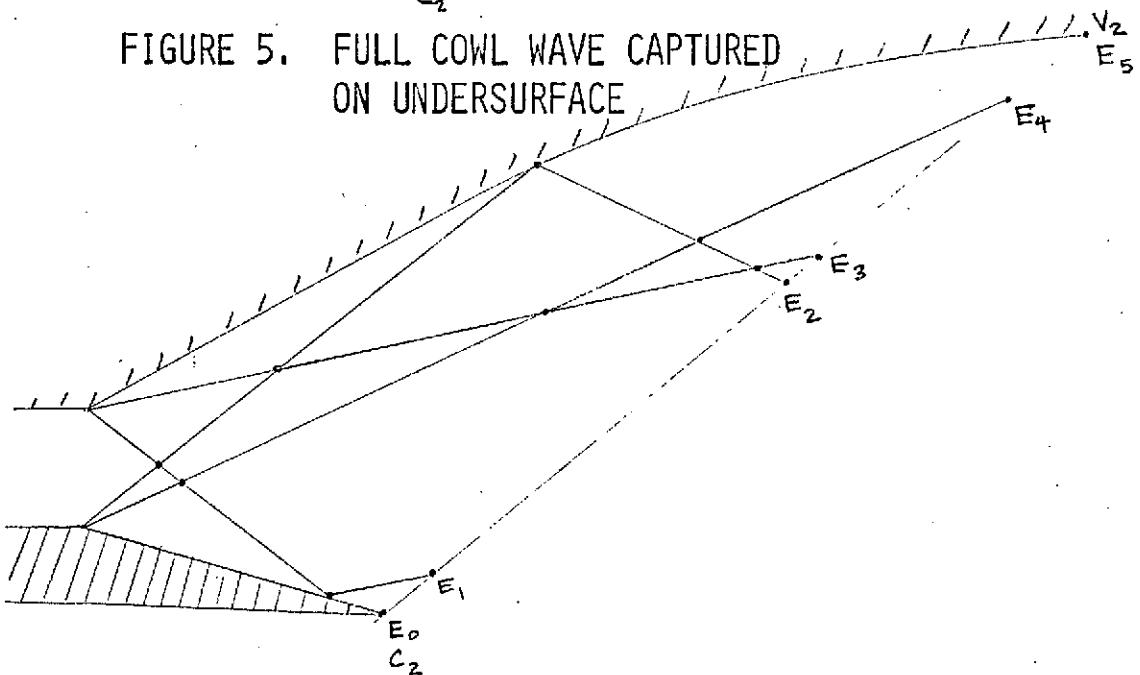


FIGURE 6. NO UNIFORM WAVE ZONE ON EXIT PLANE

TR 188

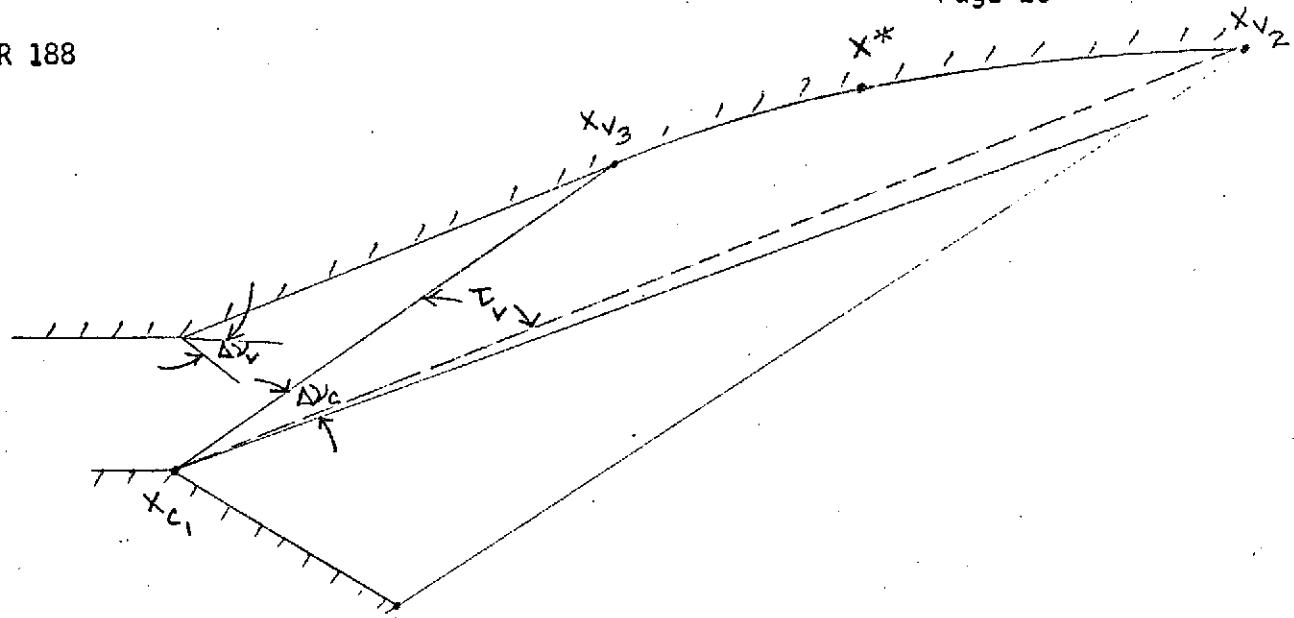


FIGURE 7. WAVE DISTRIBUTION ON UNDERSURFACE

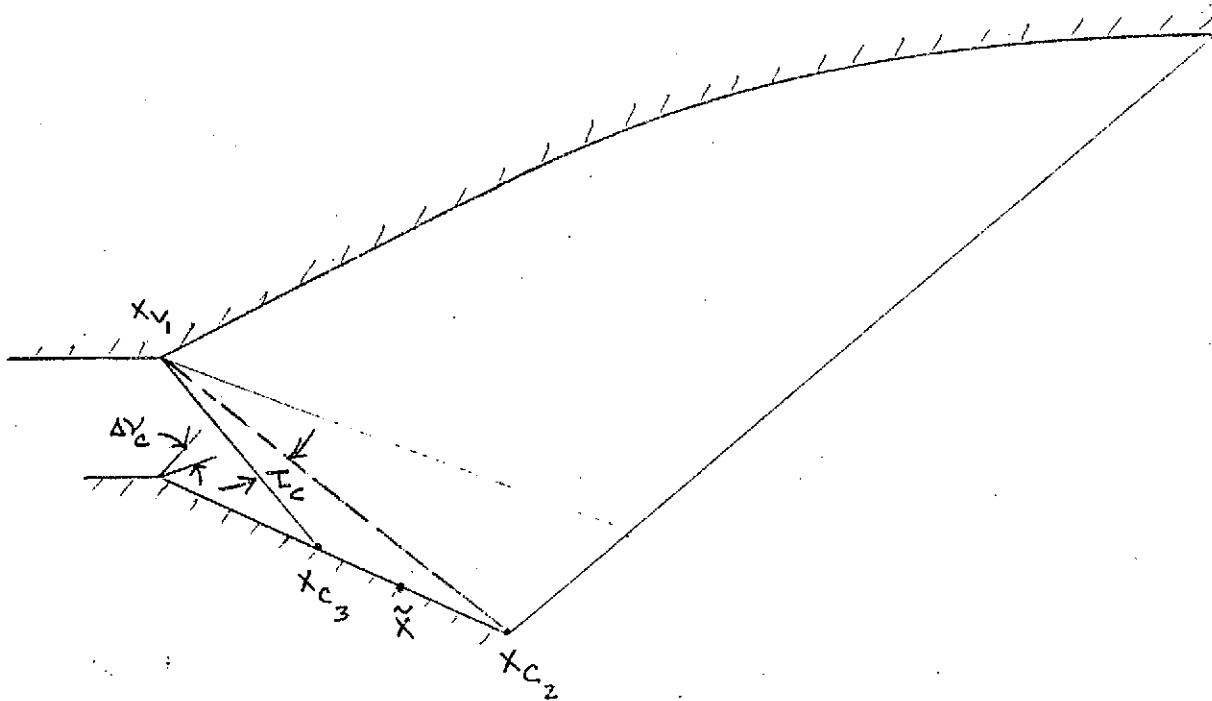


FIGURE 8. WAVE DISTRIBUTION ON COWL

$$P_i = 850 \text{ lb/ft}^2$$

$$M_i = 3$$

$$\gamma = 1.4$$

$$\Delta p = 23.1 \text{ lb/ft}^2$$

$$W = 28.96$$

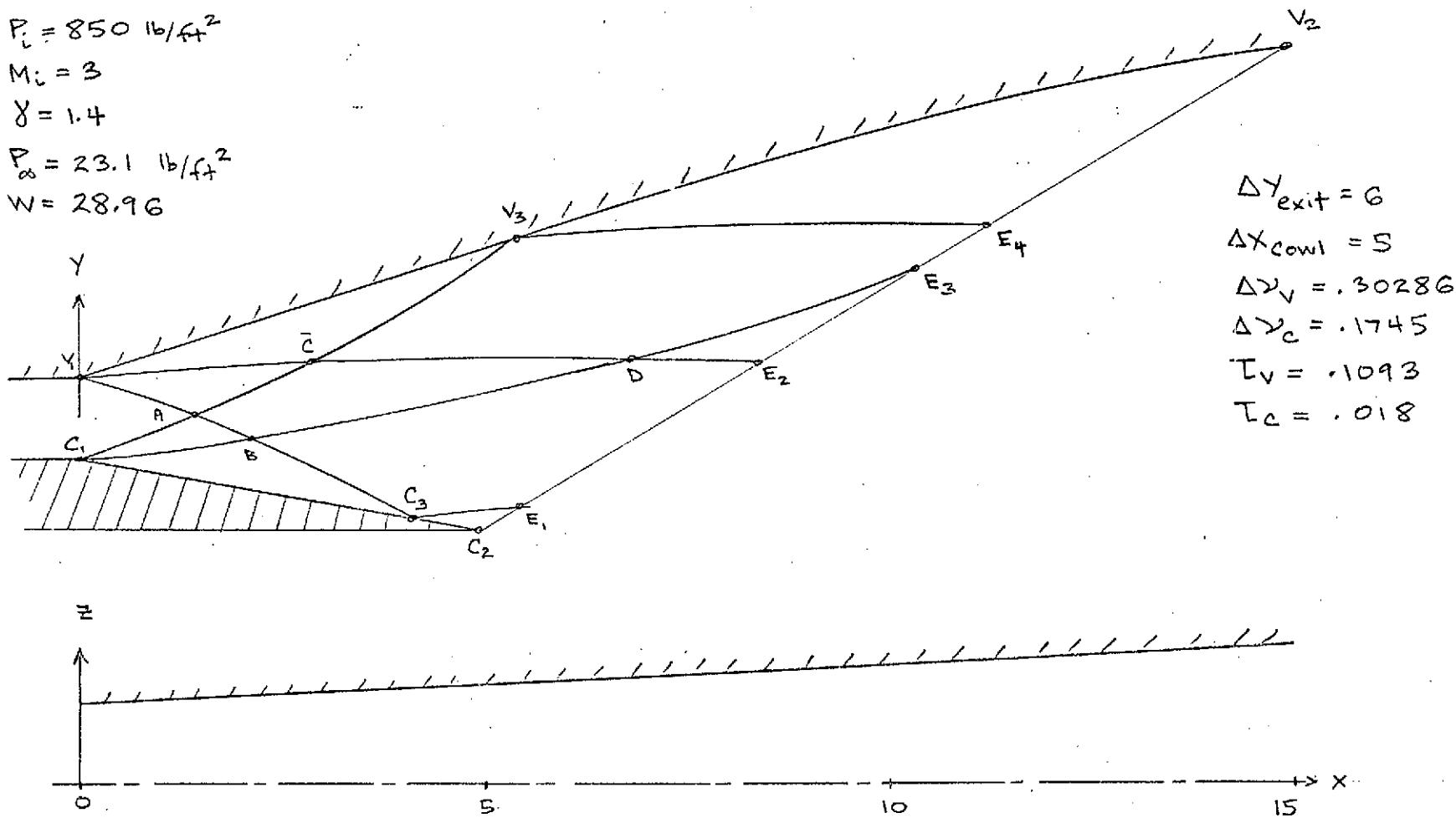


FIGURE 9. WAVE PATTERN IN THREE DIMENSIONAL COMPARISON CALCULATION

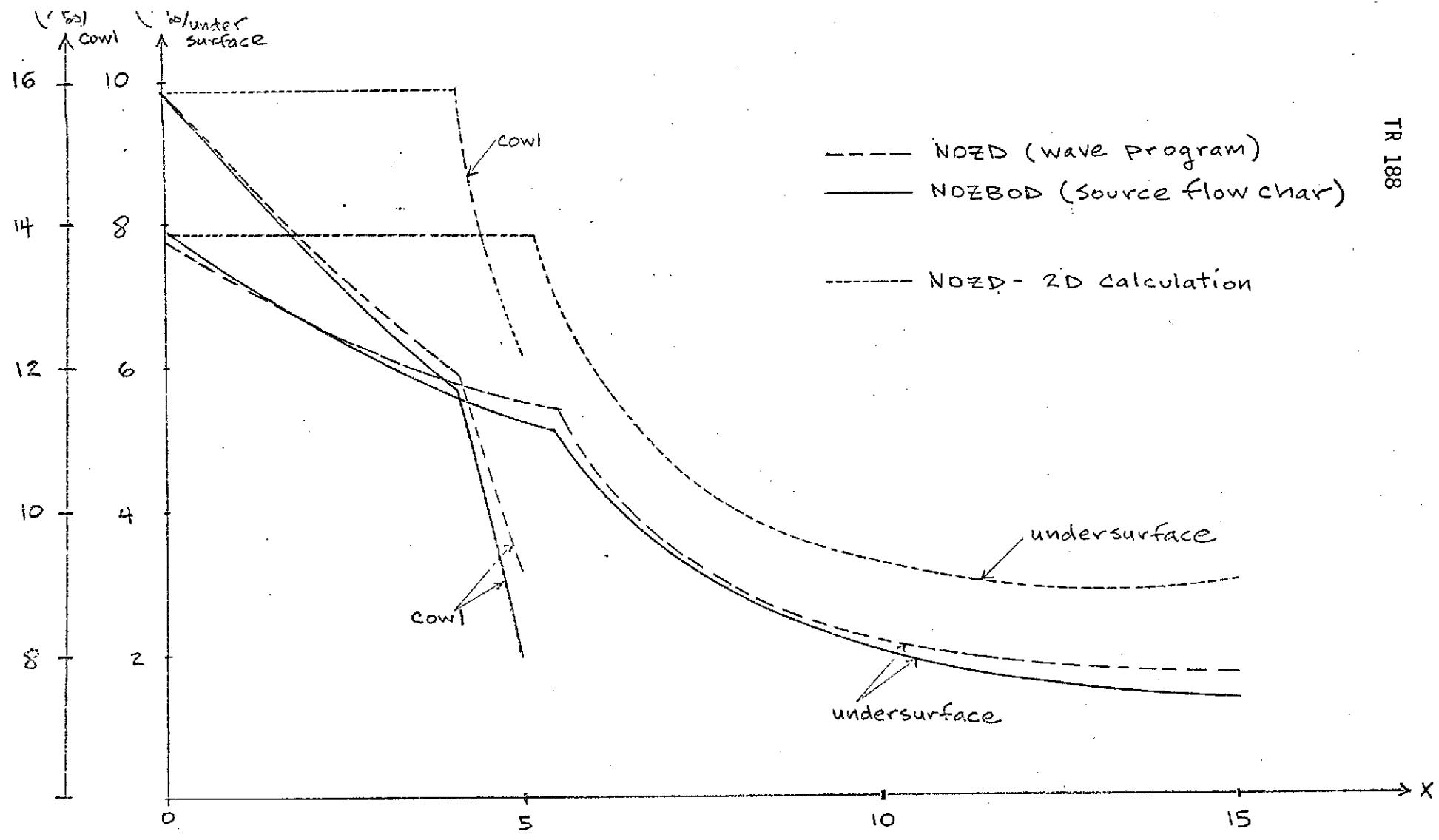


FIGURE 10. COMPARISON OF PRESSURE DISTRIBUTIONS WAVE PROGRAM VS. CHAR PROGRAM

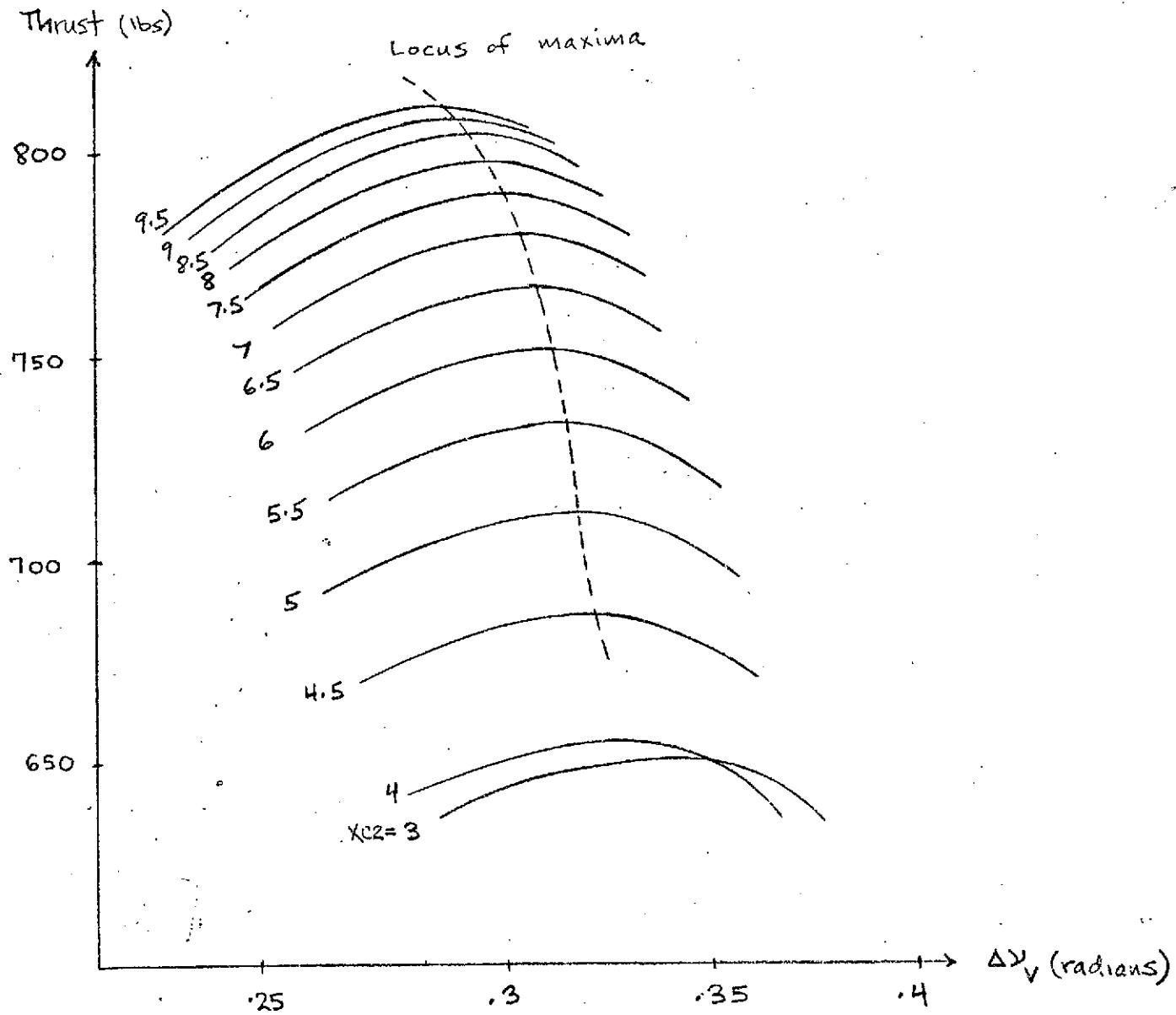


FIGURE 11. THRUST VARIATION WITH COWL LENGTH AND VEHICLE EXPANSION ANGLE

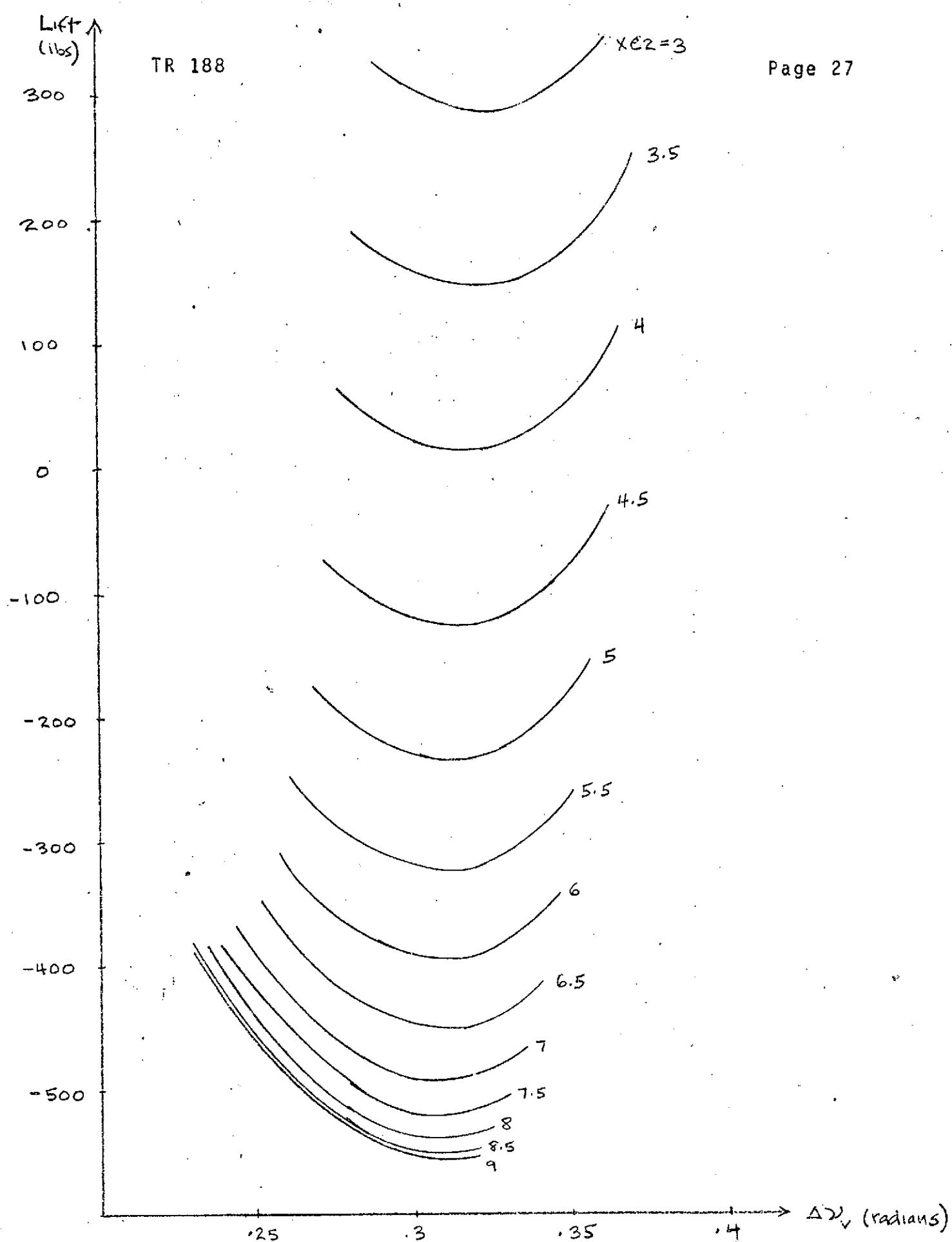


FIGURE 12. LIFT VARIATION WITH COWL LENGTH AND VEHICLE EXPANSION

XC2 = 5.0000E+00  
 DNUV = 3.0284E-01  
 DNUC = 1.7452E-01  
 TAU = 1.0927E-01  
 TAUC = 1.0778E-02  
 TAURV = 1.1235E-01  
 TAURC = 0.

PT.	X	Y	Z	THE $\theta$ A	MACH	DNU2D
V1	0.	1.0000E+00	1.0000E+00	3.0284E-01	4.1372E+00	3.0286E-01
C1	0.	0.	1.0000E+00	-1.7452E-01	3.6070E+00	1.7452E-01
A	1.4457E+00	5.0000E-01	1.0723E+00	0.	3.0971E+00	0.
B	2.1320E+00	2.1850E-01	1.1066E+00	-1.7452E-01	3.7171E+00	1.7452E-01
C	2.9043E+00	1.1829E+00	1.1452E+00	3.0284E-01	4.2930E+00	3.0286E-01
D	6.8416E+00	1.2098E+00	1.3421E+00	1.2834E-01	5.4797E+00	4.7738E-01
V3	5.4918E+00	2.7161E+00	1.2746E+00	3.0284E-01	4.4170E+00	3.0286E-01
C3	4.1220E+00	-7.2677E-01	1.2061E+00	-1.7452E-01	3.8115E+00	1.7452E-01
	NO F POINT					
	NO G POINT					

PT.	X	Y	Z	THE $\theta$ A	MACH	DNU2D	P	T
E0	5.0000E+00	-8.8157E-01	1.2500E+00	-1.7452E-01	3.9908E+00	2.1010E-01	2.1547E+02	6.7562E+02
E1	5.5189E+00	-5.7023E-01	1.2759E+00	-1.1295E-01	4.1213E+00	2.3609E-01	1.8130E+02	6.4310E+02
E2	8.3471E+00	1.1267E+00	1.4174E+00	1.2834E-01	5.5195E+00	4.7738E-01	3.4006E+01	3.9867E+02
E3	1.0361E+01	2.3349E+00	1.5180E+00	1.2834E-01	5.6112E+00	4.7738E-01	3.0791E+01	3.8751E+02
E4	1.1157E+01	2.8125E+00	1.5578E+00	1.3999E-01	5.5691E+00	4.6574E-01	3.2221E+01	3.9257E+02
E5	1.5000E+01	5.1184E+00	1.7500E+00	1.9051E-01	5.3691E+00	4.0906E-01	4.0124E+01	4.1796E+02

TABLE I DATA FOR THREE DIMENSIONAL SAMPLE CALCULATION

XC2 = 5.0000E+00  
 DNUV = 3.0286E-01  
 DNUC = 1.7452E-01  
 TAU = 1.2823E-01  
 TAUC = 2.3670E-02  
 TAURV = 1.0915E-01  
 TAURC = 0.

PT.	X	Y	Z	THETA	MACH	DNUCD
V1	0.	1.0000E+00	1.0000E+00	3.0284E-01	4.1372E+00	3.0286E-01
C1	0.	0.	1.0000E+00	-1.7452E-01	3.6070E+00	1.7452E-01
A	1.4264E+00	5.0000E-01	1.0000E+00	0.	3.0230E+00	0.
R	2.0862E+00	2.2200E-01	1.0000E+00	-1.7452E-01	3.6070E+00	1.7452E-01
C	2.8135E+00	1.1654E+00	1.0000E+00	3.0284E-01	4.1372E+00	3.0286E-01
D	6.2253E+00	1.1457E+00	1.0000E+00	1.2834E-01	5.0682E+00	4.7738E-01
V3	5.2206E+00	2.6313E+00	1.0000E+00	3.0284E-01	4.1372E+00	3.0286E-01
C3	3.9703E+00	-7.0002E-01	1.0000E+00	-1.7452E-01	3.6070E+00	1.7452E-01
NO F POINT						
G	1.0516E+01	2.6006E+00	1.0000E+00	1.2834E-01	5.0682E+00	4.7738E-01

PT.	X	Y	Z	THETA	MACH	DNUCD	P	T
E0	5.0000E+00	-8.8157E-01	1.0000E+00	-1.7452E-01	3.7908E+00	2.2188E-01	2.8241E+02	7.2992E+02
E1	5.6980E+00	-4.6278E-01	1.0000E+00	-9.0052E-02	3.9441E+00	2.5899E-01	2.2938E+02	6.8781E+02
E2	8.1527E+00	1.0100E+00	1.0000E+00	1.2834E-01	5.0682E+00	4.7738E-01	5.6430E+01	4.6074E+02
E3	1.0773E+01	2.5825E+00	1.0000E+00	1.2834E-01	5.0682E+00	4.7738E-01	5.6430E+01	4.6074E+02
E4	1.1180E+01	2.8265E+00	1.0000E+00	1.3019E-01	5.0797E+00	4.7922E-01	5.5685E+01	4.5899E+02
E5	1.5000E+01	5.1184E+00	1.0000E+00	1.9371E-01	4.9023E+00	4.5016E-01	6.8504E+01	4.8698E+02

TABLE II DATA FOR TWO DIMENSIONAL SAMPLE CALCULATION

REFERENCES

1. Dash, S., "The Determination of Nozzle Contours for Rotational, Non-Homentropic Gas Mixtures," ATL TR 148, March 1970.
2. Ferri, A., Dash, S., and Del Guidice, P., "Methodology for Three Dimensional Nozzle Design," ATL TR 195, March 1974.
3. Del Guidice, P., Dash, S. and Kalben, P., "A Source Flow Characteristic Technique for the Analysis of Scramjet Exhaust Flow Fields," ATL TR 186, March 1974.
4. Dash, S. and Del Guidice, P., "Three Dimensional Nozzle-Exhaust Flow Field Analysis by a Reference Plane Technique," AIAA Paper No. 72-704, June 1972.
5. Dash, S. and Del Guidice, P., "Analysis and Design of Three Dimensional Supersonic Nozzles," ATL TR 166, October 1972.

APPENDIX I  
PROGRAM DESCRIPTION

#### A. Input

Card 1 (Format 8E10.0)

Column 1-10 P (initial pressure, lb/ft<sup>2</sup>)  
 11-20 Th (initial flow deflection angle, radians)  
 21-30 EM (initial Mach number) - frozen for frozen deck, equilibrium for  
 31-40 T (initial temperature, degrees Rankine)

\* For Frozen Deck

41-50 G (specific heat ratio  $\gamma$ ) - frozen)  
 51-60 WGAS (molecular weight)  
 61-70 PINF (external pressure  $P_\infty$ ,  $1b/ft^2$ )

\* For Equilibrium Deck

41-50 PHI (fuel-air equivalence ratio  $\phi$ )  
 51-60 PINF (external pressure  $P_\infty$ ,  $\text{lb}/\text{ft}^2$ )

Card 2 (Format 8E10.0)

Column 1-10	XV1 ( $X_{V_1}$ of Figure 1, ft)
11-20	YV1 ( $Y_{V_1}$ )
21-30	XV2 ( $X_{V_2}$ )
31-40	XC1 ( $X_{C_1}$ )
41-50	YC1 ( $Y_{C_1}$ )
51-60	XC2 ( $X_{C_2}$ )
61-70	DYV (vehicle exit height $Y_{V_2} - Y_{C_2}$ )
71-80	DNUC ( $\Delta v_C$ -cowl turning angle-degrees)

Card 3

Column 1-5 (I5) ICF-number of different cowl lengths to be executed  
 6-15 (E10.0) DXC-increment to be added to original cowl length  $X_{C_2}$   
 16-20 (I5) JTF-number of vehicle turning angles to be run for each cowl length  
 21-30 (E10.0) DTH-increment for vehicle turning angle in degrees  
 31-35 (I5) IPR-print option  
 IPR=0 prints properties on undersurface and cowl  
 IPR=1 suppresses above printout  
 36-40 (I5) IPOLY-polynomial print option  
 IPOLY=0 prints polynomial coefficients of wall surfaces in form suitable for running program NOZBOD  
 (Reference 3)  
 IPOLY=1 suppresses above printout

Card 4 (8E10.0)

Column 1-10 XSHF (X location of origin for moment calculation)  
 11-20 YSHF (Y location of moment origin)

Card 5 (8E10.0)

Column 1-10 AZ coefficients of lateral expansion quadratic  
 11-20 BZ  
 21-30 CZ  $Z(X) = AZ*X^2 + BZ*X + CZ$   
 (where  $Z(X)$  is ratio of lateral nozzle extent at X station to that at initial station)

B. Output

The output is readily understood by referring to the figures in the report. If the F point or G point falls downstream of the nozzle exit station  $E_0-E_5$ , this is indicated in the printout by "No F Point" or "No G Point" respectively. If there is no uniform two dimensional wave zone, the exit line is not computed. The percentage thrust loss is based on the calculation of the ideal thrust using one dimensional considerations based on the entrance and exit area projections onto planes  $X=\text{constant}$  (i.e.,  $A_{\text{exit}} = (YV_2 - YC_2) * (ZV_2 + ZC_2) / 2$ ).

3. RHEQ-density fit in equilibrium deck  $\rho = RHEQ(P, T, \Phi)$
4. FGAM-isentropic fit in equilibrium deck  $r = FGAM(P, T, \Phi)$
5. FH-static enthalpy fit in equilibrium deck  $h = FH(P, T, \Phi)$

APPENDIX IILISTING OF FROZEN FLOW PROGRAM

```

PROGRAM NOZD(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
COMMON/A/P1(3),TH1(3),EM1(3),AI(3),G1(3)
COMMON/SHF/ XSHF,YSHF
COMMON/POL/ IPR,IPOLY
COMMON/THRMAX/THRMAX
DIMENSION T1(3)
COMMON/R/XA,YA,XB,YB,XC,YC,XD,YD,
1THA,THB,THC,THD,EMA,EMB,EMC,EMH,XMUA,XMUB,XMUC,XMUD
COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
COMMON/D3/ AZ,BZ,CZ
COMMON /V/ AV,RV,CV
COMMON/P/ PINF
DIMENSION P2(10),TH2(10),EM2(10),T2(10),G2(10),X2(10),Y2(10)
1,Z2(10)
DIMENSION HOL(11),HOLE(6),DNUE(10)
DATA HOLE/2HE0,2HE1,2HE2,2HE3,2HE4,2HE5/
DATA HOL/2HV1,2HC1,2HA,2HB,2HC,2HD,2HV3,2HC3,2HF,2HG,2HV4/
GETZ(X5)=AZ*X5+BZ*X5+CZ
98 FORMAT(7E13.5)
99 FORMAT(/)
100 FORMAT(8E10.0)
READ(5,100) P1(1),TH1(1),EM1(1),T1(1),G1(1),WGAS,PINF
DO 106 I=2,3
P1(I)=P1(1) $ TH1(I)=TH1(1) $ EM1(I)=EM1(1) $ G1(I)=G1(1)
T1(I)=T1(1)
106 CONTINUE
DUM=1.+(G1(1)-1.)/2.*EM1(1)**2
PTOT=P1(1)*DUM**((G1(1)/(G1(1)-1.)))
TTOT=T1(1)*DUM
RG=49800.
RGAS=RG/WGAS
TAURG=0.
READ(5,100) XV1,YV1,XV2,XC1,YC1,XC2,DYV,DNUC
READ(5,5921) IC,F,DXC,JTF,DTH,IPR,IPOLY
5921 FORMAT(15,E10.0,15,E10.0,2I5)
READ(5,100) XSHF,YSHF
DNUC=DNUC/57.3
READ(5,100) AZ,BZ,CZ
ZC1=AZ*XC1+XC1*BZ*XC1+CZ
ZV1=AZ*XV1+XV1*BZ*XV1+CZ
ZC2=GETZ(XC2)
WRITE(6,5922)
5922 FORMAT(1H1//++)
WRITE(6,1020)
1020 FORMAT( 20X#F R O Z E N   F L O W   N O Z Z L E   D E S I G N#)
WRITE(6,400) P1(1),TH1(1),EM1(1),T1(1),G1(1),WGAS,PINF
400 FORMAT( //30X,*INITIAL PROFILE*//9X*PRESSURE*7X*THETA*8X*MACH*16X*TEMPERATURE*5X*GAMMA*7X*MOL WT*8X*INF*//7E13.5)
WRITE(6,5930) XV1,YV1,XV2,XC1,YC1,XC2,DYV
5930 FORMAT(//6X*XV1*10X*YV1*10X*XV2*10X*XC1*10X*YC1*10X*XC2*10X*DYV//17E13.5//)
WRITE(6,5923) XSHF,YSHF
5923 FORMAT(9X*MOMENT AXIS*/12X*X =*E13.5/12X*Y =*E13.5//)
WRITE(6,1001) AZ,BZ,CZ
1001 FORMAT(9X*LATERAL EXPANSION EQUATION*/9X,22HZ(X) = AZ*X**2+BZ*X+CZ1/12X*AZ =*E13.5/12X*BZ =*E13.5/12X*CZ =*E13.5)

```

```

XC22=XC2
THC1=TH1(3)-DNUC
DO 5000 IXC=1,ICF
XC2=XC22+FLOAT(IXC-1)*DXC
CALL THM(EM1(1),P1(1),G1(1),PINF,YV1,YC1,DYV,XV2,THRMAX,XC2)
WRITE(6,6364) THRMAX
6364 FORMAT(1H131X*IDEAL THRUST =#E12.4)
YC2=YC1+TAN(THC1)*(XC2-XC1)
YV2=YC2+DYV
DO 6000 JT=1,JTF
THX=1.E+10
THJT=FLOAT(JT-1)*DTH
DNUV=ATAN((YV2-YV1)/(XV2-XV1))-TH1(3)-THJT/57.3
CALL PM(EM1(1),DNUC,EMC1,G1(1))
CALL PM(EM1(1),DNUV,EMV1,G1(1))
IT2=1
1000 CONTINUE
CALL CHAR
DNUA=0.
DNUD=DNUV+DNUC
ZA=GETZ(XA)
ZR=GETZ(XB)
ZC=GETZ(XC)
ZD=GETZ(XD)
RAT=0.
THC3=THC1
CALL PM(EM1(1),DNUC,EMC3,G1(1))
CALL FIX(XC1,YC1,THC1,0.,XB,YB,THB,XMUB,XC3,YC3,THC3,XMUC3,EMC3,
1G1(1))
ZC3=GETZ(XC3)
IF(XC3.LT.XC2) GO TO 177
TAUC=0.
XC3=XC2
DNUE0=DNUC
THC2=THC1
THE0=THC2
CALL PM(EM1(1),DNUE0,EME0,G1(1))
CALL FM3D(EME0,EME0N,XC2,G1(1))
EME0=EME0N
XMUE0=ASIN(1./EME0)
GO TO 175
177 CONTINUE
IT9=1
RAT=.1
176 CONTINUE
XMUBD=XMUB+RAT*(XMUD-XMUB)
THBD=THB+RAT*(THB-THB)
XT=XR+RAT*(XD-XB)
YT=YR+RAT*(YD-YB)
TAUC=RAT*DNUV
IF(RAT.GT.1.0) GO TO 6000
DNUW=DNUC+TAUC
CALL PM(EM1(1),DNUW,EMW,G1(1))
THW=THC3+TAUC
CALL FIX(XC3,YC3,THC3,XMUC3,XT,YT,THBD,XMUBD,XW,YW,THW,XMUW,EMW,
1G1(1))

```

```

DNUE0=DNUC+2.*TAUC
THC2=THC1
THE0=THC2
CALL PM(EM1(1),DNUE0,EME0,G1(1))
CALL EM3D(EME0,EME0N,XC2,G1(1))
EME0=EME0N
XMUE0=ASIN(1./EME0)
SLWC2=(TAN(THW-XMUW)+TAN(THE0-XMUE0))/2.
YC2T=YW+SLWC2*(XC2-XW)
ER9=YC2-YC2T
IF(ABS(ER9).LT.1.E-03) GO TO 175
CALL ERROR(4,IT9,RAT,ER9,1.11,RAT1,ER91)
GO TO 176
175 CONTINUE
THV3=TH1(1)+DNUV
CALL PM(EM1(1),DNUV,EMV3,G1(1))
THV1=THV3
CALL FIX(XC,YC,THC,XMUC,XV1,YV1,THV1+0.,XV3,YV3,THV3+XMUV3,EMV3,
1G1(1))
AV=YV3 $ BV=TAN(THV3)
CV=(YV2-AV-BV*(XV2-XV3))/(XV2-XV3)**2
ZV3=GETZ(XV3)
THV2=ATAN(BV+2.*CV*(XV2-XV3))
IF(THV2.LT.0.) GO TO 462
TAURV=THV2-THV3
ITZ=1
TTAU=0
RAT=1.
545 CONTINUE
530 CONTINUE
XZ=XC+RAT*(XD-XC)
YZ=YC+RAT*(YD-YC)
TAU=RAT*DNUC
THZ=THC+RAT*(THD-THC)
EMZ=EMC+RAT*(EMD-EMC)
XMUZ=ASIN(1./EMZ)
THY=THV3-TAU
DNUY=DNUV+TAU
CALL PM(EM1(1),DNUY,EMY,G1(1))
CALL FIX(XZ,YZ,THZ,XMUZ,XV3,YV3,THV3+XMUV3,XY,YY,THY+XMUY,EMY,G1(1
1))
DNUE5=DNUV+2.*TAU+TAURV
THE5=THV2
CALL PM(EM1(1),DNUE5,EME5,G1(1))
CALL EM3D(EME5,EME5N,XV2,G1(1))
EME5=EME5N
XMUE5=ASIN(1./EME5)
SL2T=(TAN(THY+XMUY)+TAN(THE5+XMUE5))/2.
YY2T=YY+SL2T*(XV2-XY)
IF(ITZ.EQ.1).AND.YV2T.GE.YV2) GO TO 542
EZ=YV2T-YV2
IF(ABS(EZ).LT.1.E-03) GO TO 540
IF(DNUC.EQ.0.) GO TO 540
CALL ERROR(5,ITZ,RAT,EZ,1,RAT1,EZ1)
GO TO 530
542 TTAU=1

```

540 CONTINUE

```

DNUE2=DNUV+DNUC
CALL PM(EM1(1),DNUE2,EME2,G1(1))
THE2=TH1(1)+DNUV-DNUC
THF=THE2
EMF=EME2
CALL FIX(XC3,YC3,THC3,XMUC3,XD,YD,THD,XMUD,XF,YF,THF,XMUF,EMF,
1G1(1))
SLE=(YV2-YC2)/(XV2-XC2)
THE=ATAN(SLE)
EMFT=EME2
CALL FIX(XC3,YC3,THC3,XMUC3,XC2,YC2,THE,0.,XFT,YFT,THF,XMUF,EMFT,
1G1(1))
IF(XF,GT,XFT) GO TO 300
CALL FIX(XF,YF,THF,XMUF,XC2,YC2,THE,0.,XE2,YE2,THE2,XMUE2,EME2,
1G1(1))
ZF=GETZ(XF)
SLF=TAN(THF-XMUF)
CALL GEM(XF,YF,SLF,XC2,YC2,SLE,XE1,YE1)
ITE1=0

```

368 CONTINUE

```

RAT=(YE1-YC2)/(YE2-YC2)
DNUE1=DNUV+DNUC+(1.-RAT)*TAUC
CALL PM(EM1(1),DNUE1,EME1,G1(1))
THE1=TH1(1)+DNUV-DNUC-(1.-RAT)*TAUC
CALL FIX(XC2,YC2,THE,0.,XF,YF,THF,XMUF,XE1,YE1,THE1,XMUE1,EME1,
1G1(1))
IF(ITE1,EQ,1) GO TO 369
ITE1=1
GO TO 368

```

369 CONTINUE

```

GO TO 310

```

300 CONTINUE

```

CALL FIX(XC2,YC2,THE,0.,XD,YD,THD,XMUD,XE2,YE2,THE2,XMUE2,EME2,
1G1(1))
SLCE=TAN(THC3+XMUC3)
CALL GEM(XC3,YC3,SLCE,XC2,YC2,SLE,XE1,YE1)
ITE1=0

```

381 CONTINUE

```

RAT=(YE1-YC2)/(YE2-YC2)
DNUF1=DNUC+TAUC+RAT*(DNUV-TAUC)
CALL PM(EM1(1),DNUF1,EME1,G1(1))
THE1=TH1(1)-DNUC+TAUC+RAT*(DNUV-TAUC)
CALL FIX(XC3,YC3,THC3,XMUC3,XC2,YC2,THE,0.,XE1,YE1,THE1,XMUE1,EME1
1,G1(1))
TF(ITF1,EQ,1) GO TO 380
ITE1=1
GO TO 381

```

380 CONTINUE

310 CONTINUE

```

THE3=THE2
DNUE3=DNUF2
CALL PM(EM1(1),DNUE3,EME3,G1(1))
XMUE3=ASIN(1./EMF3)
TF(ITAU,NE,1) GO TO 311
XG=XY $ YG=YY $ THG=THY $ EMG=EMY $ XMUG=XMUY

```

```

XGT=XG
GO TO 3588
311 CONTINUE
THG=THE3 $ EME=EME3
CALL FIX(XD,YD,THD,XMUD,XV3,YV3,THV3,XMUV3,XG,YG,THG,XMUG,EMG,
1G1(1))
FMGT=EMF3
CALL FIX(XC2,YC2,THE,0.,XV3,YV3,THV3,XMUV3,XGT,YGT,THG,XMUGT,EMGT,
1G1(1))
IF(XG,GT,XGT) GO TO 350
3588 CONTINUE
CALL FIX(XC2,YC2,THE,0.,XG,YG,THG,XMUG,XE3,YE3,THE3,XMUE3,EME3,
1G1(1))
ZG=GETZ(XG)
IF(YE3.LE.YE2) GO TO 359
SLE4=TAN(THG+XMUG)
CALL GEM(XG,YG,SLE4,XC2,YC2,SLE,XE4,YE4)
IT4=0
358 CONTINUE
RAT=(YE4-YV2)/(YE3-YV2)
DNUE4=DNUV+DNUC+(1.-RAT)*(TAURV+TAU)
CALL PM(FM1(1),DNUE4,EME4,G1(1))
THE4=TH1(1)+DNUV+DNUC+(1.-RAT)*(TAURV+TAU)
CALL FIX(XG,YG,THG,XMUG,XC2,YC2,THE,0.,XE4,YE4,THE4,XMUE4,EME4,
1G1(1))
IF(IT4.EQ.1) GO TO 359
IT4=1
GO TO 358
359 CONTINUE
IF(ITAU.EQ.0) GO TO 360
SLV32=(YV2-YV3)/(XV2-XV3)
SLG=TAN(THG+XMUG)
CALL GEM(XV3,YV3,SLV32,XG,YG,SLG,XV4,YV4)
TTV4=1
362 YV4=AV+BV*(XV4-XV3)+CV*(XV4-XV3)**2
THV4=ATAN(BV+2.*CV*(XV4-XV3))
TAURV4=THV4-THV3
DNUV4=DNUV+5.*TAU+TAURV4
CALL PM(FM1(1),DNUV4,EMV4,G1(1))
CALL FM3D(EMV4,EMV4N,XV4,G1(1))
FMV4=FMV4N
XMUV4=ASIN(1./FMV4)
YV4T=YG+.5*(TAN(THG+XMUG)+TAN(THV4+XMUV4))*(XV4-XG)
ERV4=(YV4T-YV4)/YV2
IF(ABS(ERV4).LT.1.E-03) GO TO 361
CALL ERROR(361,ITV4,XV4,ERV4,1.1,XV41,ERV41)
ZV4=GFTZ(XV4)
IF(ITV4.EQ.1) GO TO 361
GO TO 362
361 DNUE4=DNUV4
IF(YE3.LE.YE2) GO TO 460
CALL PM(FM1(1),DNUE4,EME4,G1(1))
THE4=THV4
CALL FIX(XC2,YC2,THE,0.,XV4,YV4,THV4,XMUV4,XE4,YE4,THE4,XMUE4,
1EME4,G1(1))
GO TO 360

```

```

350 CONTINUE
  IT4=0
  CALL FIX(XD,YD,THD,XMUD,XC2,YC2,THE,0.,XE3,YE3,THE3,XMUE3,EME3,
  1G1(1))
  IF(YE3.LE.YE2) GO TO 460
  SLE4=TAN(THV3-XMUV3)
  CALL GEM(XV3,YV3,SLE4,XC2,YC2,SLE,XE4,YE4)
371 CONTINUE
  RAT=(YE4-YV2)/(YE3-YV2)
  DNUE4=DNUV+TAU+RAT*(DNUC-TAU)
  CALL PM(EM1(1),DNUE4,EME4,G1(1))
  THE4=TH1(1)+DNUV-TAU=RAT*(DNUC-TAU)
  CALL FIX(XC2,YC2,THE,0.,XV3,YV3,THV3,XMUV3,XE4,YE4,THE4,XMUE4,EME4
  1,G1(1))
  IF(IT4.EQ.1)GO TO 370
  IT4=1
  GO TO 371
370 CONTINUE
360 CONTINUE
  IF(YE3.LE.YE2) GO TO 460
  X2(1)=XC2 $ X2(2)=XE1 $ X2(3)=XE2 $ X2(4)=XE3 $ X2(5)=XE4
  X2(6)=XV2
  Y2(1)=YC2 $ Y2(2)=YE1 $ Y2(3)=YE2 $ Y2(4)=YF3 $ Y2(5)=YE4
  Y2(6)=YV2 $ EM2(1)=EME0 $ EM2(2)=EME1 $ EM2(3)=EME2 $ EM2(4)=EME3
  EM2(5)=EME4 $ EM2(6)=EME5 $ TH2(1)=THE0 $ TH2(2)=THE1
  TH2(3)=THE2 $ TH2(4)=THE3 $ TH2(5)=THE4 $ TH2(6)=THE5
  DNUE(1)=DNUE0 $ DNUE(2)=DNUE1 $ DNUE(3)=DNUE2 $ DNUE(4)=DNUE3
  DNUE(5)=DNUE4 $ DNUE(6)=DNUE5
  INDEX=0
180 CONTINUE
  DO 160 J=1*6
  DUM=1.+(G1(1)-1.)/2.*EM2(I)**2
  P2(I)=PTOT/DUM**((G1(1)/(G1(1)-1.))
  T2(I)=TTOT/DUM
  Z2(I)=A2*X2(I)**2+BZ*X2(I)+CZ
160 CONTINUE
  THS1=1.5707963
  IF(XV1.NE.XC1) THS1=ATAN((YV1-YC1)/(XV1-XC1))
  THS2=ATAN((YV2-YC2)/(XV2-XC2))
  ZI=.5*(GETZ(XC1)+GETZ(XV1))
  XMASS1=P1(1)*EM1(1)/SQRT(T1(1))*SIN(THS1-TH1(1))/SIN(THS1)*ZI*
  1(YV1-YC1)
  DUM=G1(1)*EM1(1)**2*SIN(THS1-TH1(1))/SIN(THS1)
  U=1.-PINF/P1(1)
  THX1=P1(1)*(U+DUM*COS(TH1(1)))+ZI*(YV1-YC1)
  CALL XTH(X2,Y2,TH2,UNUE,EM1,G1,PTOT,TTOT,THS2,THX1,XMASS1,THX)
  ISH=0
  GO TO 461
460 CONTINUE
  ISH=1
  WRITE(6,991)
991 FORMAT(* YE3.LE.YE2*)
461 CONTINUE
  WRITE(6,1004) XC2,DNUV,DNUC,TAU, TAUC,TAURV,TAURC
1004 FORMAT( 32X*XC2 =#E12.4/32X*DNUV =#E12.4/32X*DNUC =#E12.4/
  132X*TAU =#E12.4/ 32X*TAUC =#E12.4/32X*TAURV =#E12.4/32X*TAURC =

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```

18E12.4//)
  WRITE(6,1003)
1003 FORMAT(1X#PT,*6X*X#11X#Y#11X#Z# 8X#THETA#7X#MACH#8X#DNU2D#/)
  WRITE(6,1002)HOL(1),XV1,YV1,ZV1,THV1,FMV1,DNUV,HOL(2),XC1,YC1,
  1ZC1,THC1,EMC1,DNUC,HOL(3),XA,YA,ZA,THA,EMA,DNUA,HOL(4),XB,YB,ZB,
  1THB,EMB,DNUC,HOL(5),XC,YC,ZC,THC,EMC,DNUV,HOL(6),XD,YD,ZD,THD,EMD,
  1DNUD,HOL(7),XV3,YV3,ZV3,THV3,EMV3,DNUV,HOL(8),XC3,YC3,ZC3,THC3,
  1EMC3,DNUC
1002 FORMAT(1XA2,6E12.4)
  IF(XF.GT.XFT) WRITE(6,1005)
1005 FORMAT(20X#NO F POINT#)
  IF(XF.LE.XFT) WRITE(6,1002)HOL(9),XF,YF,ZF,THF,EMF,DNUD
  IF(XG.GT.XGT) WRITE(6,1006)
1006 FORMAT(20X#NO G POINT#)
  IF(XG.LE.XGT) WRITE(6,1002)HOL(10),XG,YG,ZG,THG,EMG,DNUD
  IF(ITAU.EQ.1) WRITE(6,1002)HOL(11),XV4,YV4,ZV4,THV4,EMV4,DNUV4
  WRITE(6,1013)
1013 FORMAT(///)
  IF(ISH.EQ.1) GO TO 7384
  WRITE(6,1007)
1007 FORMAT(1X#PT,*6X*X#11X#Y#11X#Z#8X#THETA#7X#MACH#8X#DNU2D#10X#P#11X
  1#T#/)
  WRITE(6,1010)(HOLE(I),X2(I),Y2(I),Z2(I),TH2(I),EM2(I),DNUE(I),
  1P2(I),T2(I),I=1,6)
1010 FORMAT(1XA2,8E12.4)
7384 CONTINUE
  XI=XV1
  THI=TH1(1)
  CALL POLY(XV1,YV1,THI,XV3,THV3,XV2,THV2,XC1,YC1,XC2,THC2,XI)
  CALL THRIUST(XV1,YV1,EMV1,XV3,YV3,THV3,XV2,XV4,TAU,DNUV,
  1XC1,YC1,EMC1,XC3,YC3,XC2,YC2,TAUC,DNUC,PTOT,ITAU,THX)
  WRITE(6,99)
  WRITE(6,99)
  GO TO 6000
462 CONTINUE
  WRITE(6,992)
992 FORMAT(*THV2.LT.0*)
450 CONTINUE
6000 CONTINUE
5000 CONTINUE
END

```

```
SUBROUTINE CHAR
COMMON/A/P1(3),TH1(3),EM1(3),A1(3),G1(3)
COMMON/B/XA,YA,XB,YB,XC,YC,XD,YD,
1THA,THB,THC,THD,EMA,EMB,EMC,EMD,XMUA,XMUB,XMUC,XMUD
COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
G=G1(1)
XMU1=ASIN(1./EM1(1))
EMA=EM1(1)
THA=TH1(1)
CALL FIX(XC1,YC1,TH1(1),XMU1,XV1,YV1,TH1(1),XMU1,
1XA,YA,THA,XMUA,EMA,G)
THR=THA-DNUC
CALL PM(EM1(1),DNUC,EMB,G)
EMB1=EMB
XMUB1=ASIN(1./EMB1)
CALL FIX(XC1,YC1,THB,XMUB1,XA,YA,THA,XMUA,XB,YB,THB,XMUB,EMB,G)
THC=TH1(1)+DNUV
CALL PM(EM1(1),DNUV,EMC,G)
EMC1=EMC
XMUC1=ASIN(1./EMC1)
CALL FIX(XA,YA,THA,XMUA,XV1,YV1,THC,XMUC1,XC,YC,THC,XMUC,EMC,G)
60 DNUD=DNUV+DNUC
CALL PM(EM1(1),DNUD,EMD,G)
THD=TH1(1)+DNUV-DNUC
CALL FIX(XB,YB,THB,XMUB,XC,YC,THC,XMUC,XD,YD,THD,XMUD,EMD,G)
RETURN
END
```

```

SUBROUTINE THRUST(XV1,YV1,EMV1,XV3,YV3,THV3,XV2,XV4,TAU,DUV,
 1 XC1,YC1,EMC1,XC3,YC3,XC2,YC2,TAUC,NUC,PTOT,ITAU,THX)
COMMON/A/P1(3),TH1(3),EM1(3),A1(3),G1(3)
COMMON/D3/ AZ,BZ,CZ
COMMON /V/ AV,RV,CV
COMMON/P/ PINF
COMMON/SHF/ XSHF,YSHF
COMMON/POL/ IPR,IPOLY
COMMON/THRMAX/THRMAX
COMMON/PMPM/ PMOM
100 FORMAT(8E13.5)
GETZ(X5)=AZ*X5*X5+BZ*X5+CZ
PZ(EM5)=PTOT/(1.+(G1(1)-1.)/2.+EM5**2)**(G1(1)/(G1(1)-1.))-PINF
XLIF=0.
XTH=0.
XMOM=0.
DX=(XV2-XV1)/50.
N=(XV3-XV1)/DX+1.
DXN=(XV3-XV1)/FLOAT(N)
N=N+1
CALL PM(EM1(1),DUV,EMX1,G1(1))
XA=XV1 $ YA=YV1 $ ZA=GETZ(XA)
CALL EM3D(EMX1,EMA,XA,G1(1))
PA=PZ(EMA)
PX=PA+PINF
PX=PX/PINF
IF(IPR.EQ.1) GO TO 50
WRITE(6,110)
110 FORMAT(//35X*VEHICLE UNDERSURFACE*/7X*X#12X#Y#12X#Z#9X#P/PINF#
1RX*MACH#QX#LIFT#BX#THRUST#7X#MOMENT#)
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
50 CONTINUE
DO 10 I=2,N
XB=XA+DXN
YB=YV1*(XB-XV1)/(XV3-XV1)*(YV3-YV1)
ZB=GETZ(XB)
CALL EM3D(EMX1,EMB,XB,G1(1))
PB=PZ(EMB)
DUM=(PA+PB)*(ZA+ZB)/4.
DXLF=DUM*(XB-XA)
DXTH=DUM*ABS(YB-YA)
YRB=(YA+YB)/2.-YSHF
XRB=-(XA+XB)/2.-XSHF
DXMOM=-YRB*DXTH+XRB*DXLF
XLIF=XLIF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PB
EMA=EMB
PX=PA+PINF
PX=PX/PINF
IF(IPR.EQ.1) GO TO 51
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
51 CONTINUE
10 CONTINUE
N=(XV2-XV3)/DX+1.

```

```

DXN=(XV2-XV3)/FLOAT(N)
N=N+1
DO 20 I=2,N
XB=XA+DXN
YB=AV+BV*(XB-XV3)+CV*(XB-XV3)**2
ZR=GETZ(XB)
THR=ATAN(BV+2.*CV*(XB-XV3))
TAURB=THR-THV3
RATB=(XB-XV3)/(XV2-XV3)
IF (ITAU.EQ.1) RATB=(XB-XV3)/(XV4-XV3)
IF (RATB.GT.1.) RATB=1.
DNUB=DNUV+TAURB+2.*RATB*TAU
X1=XV3 $ X2=XV2
IF (ITAU.EQ.1) X2=XV4
RATA=((X1-XC1)/(XB-XC1)-1.)/((X1-XC1)/(X2-XC1)-1.)
IF (RATA.GE.1.) RATA=1.
TAUX=ATAN(RATA+TAN(TAU))
DNUB=DNUV+TAURB+2.*TAUX
CALL PM(EM1(1),DNUB,EMX,G1(1))
CALL FM3D(EMX,EMB,XB,G1(1))
PB=PZ(EMB)
DUM=(PA+PB)*(ZB+ZA)/4.
DXLF=DUM*(XB-XA)
DXTH=DUM*ABS(YB-YA)
YBB=(YA+YB)/2.-YSHF
XBB=(XA+XB)/2.-XSHF
DXMOM=-YBB*DXTH+XBB*DXLF
XLIF=XLIF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PB
EMA=EMB
PX=PA+PINF
PX=PX/PINF
IF (IPR.EQ.1) GO TO 52
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
52 CONTINUE
20 CONTINUE
XLV=XLIF
XTHV=XTH
XMOMV=XMOM
WRITE(6,101)
101 FORMAT(/)
XA=XC1 $ YA=YC1 $ ZA=GETZ(XA)
XLIF=0.
XTH=0.
XMOM=0.
N=(XC3-XC1)/Dx+1.
DXN=(XC3-XC1)/FLOAT(N)
N=N+1
CALL PM(EM1(1),DNUC,EMY1,G1(1))
CALL FM3D(EMY1,EMA,XA,G1(1))
PA=PZ(EMA)
PX=PA+PINF
PX=PX/PINF
IF (IPR.EQ.1) GO TO 53

```

```

      WRITE(6,111)
111 FORMAT(//50X*COWL#           /7X*X#12X*Y#12X*Z#9X#P/PINF#
      1RX*MACH#9X*LIFT#8X*THRUST#7X*MOMENT#)
      WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM

53 CONTINUE
DO 30 I=2,N
XB=XA+DXN
YB=YC1+(XB-XC1)/(XC3-XC1)*(YC3-YC1)
ZB=GETZ(XB)
CALL EM3D(EMY1,EMB,XB,G1(1))
PB=PZ(EMR)
DUM=(PA+PB)*(ZR+ZA)/4.
DXLF=-DUM*(XB-XA)
DXTH=DUM*ABS(YR-YA)
YBB=(YA+YB)/2.-YSHF
XBB=-((XA+XB)/2.-XSHF)
DXMOM=YBB*DXTH+XBB*DXLF
XLIF=XLIF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PB
EMA=EMB
PX=PA+PINF
PX=PX/PINF
IF(IPR.EQ.1) GO TO 54
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM

54 CONTINUE
30 CONTINUE
N=(XC2-XC3)/DX+1.
IF(N.EQ.1) GO TO 60
DXN=(XC2-XC3)/FLOAT(N)
N=N+1
DO 40 I=2,N
XB=XA+DXN
YB=YC3+(XB-XC3)/(XC2-XC3)*(YC2-YC3)
ZB=GETZ(XB)
RAT=(XB-XC3)/(XC2-XC3)
DNUB=NUC+RAT*2.*TAUC
RATA=((XC3-XV1)/(XB-XV1)-1.)/((XC3-XV1)/(XC2-XV1)-1.)
TAUY=ATAN(RATA*TAN(TAUC))
DNUB=NUC+2.*TAUY
CALL PM(EM1(1),DNUB,EMX,G1(1))
CALL EM3D(EMX,EMB,XB,G1(1))
PB=PZ(EMR)
DUM=(PA+PB)*(ZR+ZA)/4.
DXLF=-DUM*(XB-XA)
DXTH=DUM*ABS(YR-YA)
YBB=(YA+YB)/2.-YSHF
XBB=-((XA+XB)/2.-XSHF)
DXMOM=YBB*DXTH+XBB*DXLF
XLIF=XLIF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PB
EMA=EMB
PX=PA+PINF

```

```
PX=PX/PINF
IF(IPR.EQ.1) GO TO 55
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
55 CONTINUE
40 CONTINUE
60 CONTINUE
XTH=XTH+XTHV
XLIF=XLIF+XLV
XMOM=XMOM+XMOMV
WRITE(6,4203) XLIF
4203 FORMAT(//20X*TOTAL LIFT =#E12.4)
WRITE(6,1008) XTH
1008 FORMAT(//20X*THRUST (FROM COWL AND VEHICLE UNDERSURFACE) =#E12.4)
WRITE(6,4206) XMOM
4206 FORMAT(//20X*MOMENT (FROM COWL AND VEHICLE UNDERSURFACE) =#E12.4)
IF(THX.LT.1.E+09) GO TO 4201
WRITE(6,4200)
4200 FORMAT(//20X*EXIT PROFILE AND THRUST AND MOMENT (FROM SIDE WALLS, NOT CALCULATED.))
GO TO 4212
4201 IF(THX.GT.0.) GO TO 4205
WRITE(6,4204) THX
4204 FORMAT(//20X*THRUST (FROM SIDE WALLS) =#E12.4)
PMOM1=0.
WRITE(6,4211) PMOM1
4211 FORMAT(//20X*MOMENT (FROM SIDE WALLS) =#E12.4)
GO TO 4212
4205 DTHQ=THX-XTH
WRITE(6,4204) DTHQ
XTH=THX
PMOM1=PMOM-XMOM
WRITE(6,4211) PMOM1
4212 CONTINUE
PTHL=(THRMAX-XTH)/THRMAX*100.
WRITE(6,1563) PTHL
1563 FORMAT(//40X*PERCENT THRUST LOSS =#F6.3)
RETURN
END
```

```
SUBROUTINE THM(EM1,P1,G,PINF,YV1,YC1,DYV,XV2,THRMAX,XC2)
COMMON/D3/AZ,BZ,CZ
Z=AZ*XV2**2+BZ*XV2*CZ
A1=YV1-YC1
Z2=AZ*XC2**XC2+BZ*XC2*CZ
A2=DYV*(Z+Z2)/2.
FM1=1.+(G-1.)/2.*EM1**2
DUM=(2.*FM1/(G+1.))**((G+1.)/2./(G-1.))
AST=A1*EM1/DUM
PTOT=P1/FM1**(G/(1.-G))
EM2=EM1*SQRT(A2/A1)
IF(EM1.GT.3.)EM2=(A2/A1)**.3*EM1
AF=A2/AST
ITM=0
10 CONTINUE
FM2=1.+(G-1.)/2.*EM2**2
DUM=(2.*FM2/(G+1.))**((G+1.)/2./(G-1.))
AFT=DUM/EM2
ERA=(AFT-AF)/AF
IF(ABS(ERA).LT.1.E-03) GO TO 20
CALL FRROR(2000,ITM,EM2,ERA,1.1,EM21,ERA1)
GO TO 10
20 CONTINUE
F1=P1*A1*(1.+G*EM1**2)
P2=FM2**(G/(1.-G))*PTOT
F2=P2*A2*(1.+G*EM2**2)
THRMAX=F2-F1-PINF*(A2-A1)
RETURN
END
```

```

SUBROUTINE XTH(X2,Y2,TH2,DNUE,FM1,G1,PTOT,TTOT,THS2,
1THX1, XMASS1,THX)
DIMENSION XNU(50),X(50),Y(50),Z(50),EM(50),P(50),TH(50),T(50)
COMMON/P /PINP
COMMON/D3/AZ,BZ,CZ
COMMON/SHF/XSHF,YSHF
COMMON/PMOM/ PMOM
DIMENSION DNUE(10),X2(10),Y2(10),TH2(10),EM1(03),G1(03)
GETZ(X5)=AZ*X5+BZ*X5+CZ
THX=0.
IF(AZ+BZ.EQ.0.) RETURN
INDEX=0
180 CONTINUE
DO 10 I=1,5
J1=(I-1)*5+1
J2=I*5
IF(I.EQ.5) J2=26
DO 20 J=J1,J2
IF(INDEX,EQ.1) GO TO 86
RAT=FM1*FLOAT(J-J1)/FLOAT(J2-J1)
XNU(J)=DNUE(I)+RAT*(DNUE(I+1)-DNUE(I))
X(J)=X2(I)+RAT*(X2(I+1)-X2(I))
Y(J)=Y2(I)+RAT*(Y2(I+1)-Y2(I))
TH(J)=TH2(I)+RAT*(TH2(I+1)-TH2(I))
CALL PM(EM1(1),XNU(J),EM(J),G1(1))
CALL FM3D(EM(J),EMX,X(J),G1(1))
EM(J)=EMX
Z(J)=GETZ(X(J))
86 CONTINUE
DUM=1.+G1(1)-1.)/2.*EM(J)*EM(J)
DG=G1(1)/(G1(1)-1.)
P(J)=PTOT/DUM*DG
T(J)=TTOT/DUM
20 CONTINUE
10 CONTINUE
DUM=G1(1)*EM(1)**2*SIN(THS2-TH(1))/SIN(THS2)
F1=P(1)*FM(1)/SQRT(T(1))*SIN(THS2-TH(1))/
1SIN(THS2)*Z(1)
U=1.-PINP/P(1)
F1=P(1)*(U+DUM*COS(TH(1)))*Z(1)
W1=P(1)*(U/TAN(THS2)+DUM*SIN(TH(1)))*Z(1)
XMASS2=0.
THX2=0.
PMOM=0.
DO 150 J=2,26
E2=P(1)*FM(1)/SQRT(T(1))*Z(1)
F2=P(1)*FM(1)/SQRT(T(1))*Z(1)
DUM=G1(1)*EM(1)**2*SIN(THS2-TH(1))/SIN(THS2)
U=1.-PINP/P(1)
F2=P(1)*(U+DUM*COS(TH(1)))*Z(1)
W2=P(1)*(U/TAN(THS2)+DUM*SIN(TH(1)))*Z(1)
THX2=THX2+.5*(F1+F2)*(Y(I)-Y(I-1))
XMASS2=XMASS2+.5*(E1+E2)*(Y(I)-Y(I-1))
DUM1=.5*(F1*(Y(I-1)-YSHF)+F2*(Y(I)-YSHF))
DUM2=.5*(W1*(X(I-1)-XSHF)+W2*(X(I)-XSHF))
PMOM=PMOM+(DUM1+DUM2)*(Y(I)-Y(I-1))

```

```
E1=E2 $ F1=F2 $ W1=W2
150 CONTINUE
100 FORMAT(7E13.5)
      RATM=XMASS2/XMASS1
      EMS=RATM-1
      IF(ABS(EMS).LT.1.E-03)GO TO 4625
      INDEX=INDEX+1
      IF(INDEX.GT.1)GO TO 4625
      DO 170 I=1,26
      FM1=FM(EM(I),G1(1))
      FM2=FM1/RATM
      ITM=J
      EMT=EMT*EM(I)
197  CONTINUE
      FMT=FM(EMT,G1(1))
      FRM=(FM2-FMT)/FM2
      IF(ABS(FRM).LT.1.E-03)GO TO 171
      DUMD=1./RATM
      CALL ERROR(6,ITM,EMT,FRM,DUMD,EMT1,FRM1)
      GO TO 197
171  CONTINUE
      EM(I)=EMT
170  CONTINUE
      GO TO 180
4625 CONTINUE
      THX=THX2-THX1
      RETURN
      END
```

```
SUBROUTINE EM3D(EM,EMX,X,G)
COMMON/D3/ AZ,BZ,CZ
Z=AZ*X*BZ*CZ
GN=(G+1.)/(G-1.)/2.
Y=(1.+ (G-1.)/2.*FM*EM)**GN
Y=Y/EM/((G+1.)/2.)*GN
A=Y*Z
EMX=EM*SQRT(Z)
ITM=1
10 AT=(1.+ (G-1.)/2.*EMX*EMX)**GN
AT=AT/EMX/((G+1.)/2.)*GN
ERM=(AT-A)/A
IF(ABS(ERM).LT.1.E-03) GO TO 20
CALL ERROR(10, ITM,EMX,ERM,1.1,EMX1,ERM1)
GO TO 10
20 CONTINUE
RETURN
END
```

```
SUBROUTINE FIX(X1,Y1,TH1,XMU1,X2,Y2,TH2,XMU2,X3,Y3,TH3,XMU3,EM3,G)
SL1=TAN(TH1+XMU1)
SL2=TAN(TH2-XMU2)
CALL GEM(X1,Y1,SL1,X2,Y2,SL2,X3,Y3)
ITM=0
10 CONTINUE
CALL EM30(EM3,EM3N,X3,G)
XMU3=ASIN(1./EM3N)
SL13=SL1/2+.5*TAN(TH3+XMU3)
IF(XMU1.EQ.0.)SL13=SL1
SL23=SL2/2+.5*TAN(TH3-XMU3)
IF(XMU2.EQ.0.)SL23=SL2
CALL GEM(X1,Y1,SL13,X2,Y2,SL23,X3,Y3)
IF(ITM.EQ.1) GO TO 20
ITM=1
GO TO 10
20 EM3=EM3N
RETURN
END
```

```
SUBROUTINE PM (EM1,DNU,EM2,G)
GG=SORT((G+1.)/(G-1.))
XM1=SQRT(EM1**2-1.)
XNU1=GG*ATAN(XM1/GG)-ATAN(XM1)
EM2=DNU/(1.5-XNU1)*(6.-EM1)+EM1
IT3=1
10 XM2=SORT(EM2**2-1.)
DNU1=GG*(ATAN(XM2/GG)-ATAN(XM1/GG))+ATAN(XM1)-ATAN(XM2)
ERNU=DNU-DNU1
IF(ABS(ERNU).LT.1.E-04) GO TO 20
CALL ERROR(3,IT3,EM2,ERNU,1.11,EM21,ERNU1)
GO TO 10
20 CONTINUE
RETURN
END
```

```

SUBROUTINE POLY(XV1,YV1,TH1,XV3,THV3,XV2,THV2,
1XC1,YC1,XC2,THC2,X1)
COMMON/V/A11,A12,A13,A21,A22,A23,A31,A32,A33
COMMON/POL/ IPR,IPOLY
DIMENSION X(10),Y(10),TH(10)
IF(IPOLY.EQ.1) GO TO 20
IT=0
X(1)=XV1
X(2)=XV1+.01*(XV2-XV1)
X(3)=XV3
X(4)=XV2
TH(1)=TH1
TH(2)=THV3
TH(3)=THV3
TH(4)=THV2
TH(1)=-TH(1) $ TH(2)=-TH(2) $ TH(3)=-TH(3) $ TH(4)=-TH(4)
Y(1)=YC1
N=3
WRITE(6,100)
100 FORMAT(//30X*VEHICLE COORDINATES*/
115X*X*4X*T0*4X*X*15X*COORDINATES*)
30 DO 10 I=1*N
X2=X(I+1)-X1
X1=X(I)-X1
A=(TAN(TH(I+1))-TAN(TH(I)))/2.,/(X2-X1)
B=TAN(TH(I+1))-2.*A*X2
C=Y(I)-B*X1-A*X1*X1
Y(I+1)=A*X2*X2+B*X2+C
WRITE(6,64) X(I),X(I+1),A,B,C
69 FORMAT(10X5E11.3)
10 CONTINUE
IF(IT.EQ.1) GO TO 20
IT=1
X(1)=XC1 X(2)=X(1)+.01*(XV2-XV1)
X(3)=XC2
TH(2)=THC2
TH(3)=TH(2)
TH(2)=-TH(2) $ TH(3)=-TH(3)
Y(1)=YV1
N=2
WRITE(6,101)
101 FORMAT(//30X*COVL COORDINATES*/
115X*X*4X*T0*4X*X*15X*COORDINATES*)
GO TO 30
20 CONTINUE
RETURN
END

```

```
SUBROUTINE GEM(XA,YA,SLA,XB,YB,SLB,XC,YC)
XC=(YB-YA+SLA*XA-SLB*X B)/(SLA-SLB)
YC=YA+SLA*(XC-XA)
RETURN
END
```

```
SUBROUTINE ERROR (I,IT,X,ER,F,X1,ER1)
IT=IT+1
IF(IT.LT.15) GO TO 12
WRITE(6,13)
13 FORMAT(*ERROR TEST NUMBER *)
WRITE (6,20) I
20 FORMAT(I5)
STOP
12 IF(IT.GT.2) GO TO 14
ER1=ER
X1=X
X=X*F
IF(X.EQ.X1) X=X+.02
RETURN
14 XD=X1-ER1*(X-X1)/(ER-ER1)
ER1=ER
X1=X
X=XD
RETURN
END
```

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APPENDIX III

LISTING OF EQUILIBRIUM FLOW PROGRAM

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PROGRAM NOZD(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
COMMON/A/ PI,THI,EMI,GI,TI,HI,PHI,UI
COMMON/B/XA,YA,XR,YB,XC,YC,XD,YD,
1THA,THB,THC,THR,EMA,EMB,EMC,EMD,XMUA,XMUB,XMUC,XMUD
COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUC
COMMON/D/ PHI
COMMON/BR/PA,PR,PC,PD,TA,TB,TC,TD,GA,GB,GC,GD,UA,UB,UC,UD,RHA,
1RHG,RHC,RHD
COMMON/D3/ AZ,BZ,CZ
COMMON/V/AV,BV,CV
COMMON/P/PINF
COMMON/SHF/XSHF,YSHF
COMMON/POL/IPR,IPOLY
COMMON/THRMAX/THRMAX
DIMENSION P2(10),TH2(10),EM2(10),T2(10),G2(10),X2(10),Y2(10)
1,Z2(10),RH2(10),U2(10)
DIMENSION HOL(11),HOLE(6),DNUE(10)
DATA HOLE/2HE0,2HE1,2HE2,2HE3,2HE4,2HE5/
DATA HOL/2HV1,2HC1,2HA,2HB,2HC,2HD,2HV3,2HC3,2HF,2HG,2HV4/
GETZ(X5)=AZ*X5+BZ*X5+CZ
98 FORMAT(7E13.5)
99 FORMAT(/)
100 FORMAT(AB10.0)
READ(5,100) PI,THI,EMI,TI,PHI,PINF
HI=FH(PI,PHI,TT)
GI=FGAM(TI,PI,PHI)
RHI=RHEQ(HI,PI,PHI,TT)
AI=SORT(GI*PI/RHI)
UI=EMI*AI
TAURC=0.
READ(5,100) XV1,YV1,XV2,XC1,YC1,XC2,DYV,DNUC
DNUC=DNUC/57.3
READ(5,5921) IC,F,DXC,JTF,DTH,IPR,IPOLY
5921 FORMAT(15,E10.0,15,E10.0,2I5)
READ(5,100) XSHF,YSHF
READ(5,100) AZ,BZ,CZ
ZC1=GETZ(XC1)
ZV1=GETZ(XV1)
ZC2=GETZ(XC2)
WRITE(6,5922)
5922 FORMAT(1H1//++)
WRITE(6,1020)
1020 FORMAT(14X,E Q U I L I B R I U M F L O W N O Z Z L E D E
1 S I G N)
WRITE(6,400) PI,THI,EMI,TI,PHI,PINF
400 FORMAT(//30X,*INITIAL PROFILE*/3X*PRESSURE*6X*THETA*9X*MACH*
16X*TEMPERATURE*6X*PHI*9X*PINF*/6E13.5)
WRITE(6,5930) XV1,YV1,XV2,XC1,YC1,XC2,DYV
5930 FORMAT(//6X*XV1*10X*YV1*10X*XV2*10X*X1*10X*Y1*10X*X2*10X*DYV*/17E13.5//)
WRITE(6,5923) XSHF,YSHF
5923 FORMAT(9X*MOMENT AXIS*/12X*X ==E13.5/12X*Y ==E13.5//)
WRITE(6,1001) AZ,BZ,CZ
1001 FORMAT(9X*LATERAL EXPANSION EQUATION*/9X*22HZ(X) = AZ*X**2+BZ*X+CZ
1/12X*AZ ==E13.5/12X*BZ ==E13.5/12X*CZ ==E13.5)
XC22=YC2

```

```

THC1=THI    =DNUC
YC2=YC1+TAN(THC1)*(XC2-XC1)
YV2=YC2+DYV
DNUV=ATAN((YV2-YV1)/(XV2-XV1))-THI
DO 5000 IXC=1,ICF
XC2=YC22+FLOAT(IXC-1)*DXC
CALL THM(RHI,UT,PI,PINF,YV1+YC1,DYV,XV2,THRMAX,DNUC,DNUC,XC2)
WRITE(6,6364) THRMAX
6364 FORMAT(1H131X*JDEAL THRUST =*E12.4)
YC2=YC1+TAN(THC1)*(XC2-XC1)
YV2=YC2+DYV
DO 6000 JT=1,JTF
THX=1.E+10
THJT=FLOAT(JT-1)*DTH
DNUV=ATAN((YV2-YV1)/(XV2-XV1))-THI+THJT/57.3
CALL PM(DNUC,PC1,TC1,EMC1,GC1,IC1,RHC1)
CALL PM(DNUV,PV1,TV1,EMV1,GV1,UV1,RHV1)
JT2=1
1000 CONTINUE
CALL CHAR
DNUA=0.
DNUD=DNUV+DNUC
ZA=GETZ(XA)
ZB=GETZ(XB)
ZC=GETZ(XC)
ZD=GETZ(XD)
RAT=0.
THC3=THC1
CALL PM(DNUC,PC3,TC3,EMC3,GC3,IC3,RHC3)
CALL FIX(XC1,YC1,THC1,0.,XR,YB,THB,XMUB,XC3,YC3,THC3,XMUC3,EMC3,
1GC3,
1PC3,TC3,RHC3,UC3,DNUC)
ZC3=GETZ(XC3)
IT176=0
IF(XC3.LT.XC2) GO TO 177
IT176=1
TAUC=0.
XC3=XC2
DNUC0=DNUC
GO TO 178
177 CONTINUE
IT9=1
RAT=.1
176 CONTINUE
XMUBD=XMUB+RAT*(XMUD-XMUB)
THBD=THR+RAT*(THD-THB)
XT=XR+RAT*(XD-XB)
YT=YB+RAT*(YD-YB)
TAUC=RAT*DNUV
DNUW=DNUC+TAUC
CALL PM(DNUW,PW,TW,EMW,GW,UW,RHW)
THW=THC3+TAUC
CALL FIX(XC3,YC3,THC3,XMUC3,XT,YT,THBn,XMUBD,XW,YW,THW,XMUW,EMW,
1GW,
1PW,TW,RHW,UW,DNUW)
DNUC0=DNUC+2.*TAUC

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```

178 CONTINUE
  THC2=THC1
  THE0=THC2
  CALL PM(DNUE0,PE0,TE0,EME0,GE0,UE0,RHE0)
  ZE0=GETZ(XC2)
  RQ3D=RHE0*UE0/ZE0
  DNU3E=DNUE0*SQRT(ZE0)
  ITE0=1
200 CONTINUE
  CALL PM(DNU3E,PE0,TE0,EME0,GE0,UE0,RHE0)
  RQ3T=RHE0*UE0
  ERQE=(RQ3T-RQ3D)/RQ3D
  IF(ABS(ERQE).LT.1.E-03) GO TO 210
  CALL ERROR(200,ITE0,DNU3E,ERQE,1.1,DNU3E1,ERQE1)
  GO TO 200
210 CONTINUE
  XMUE0=ASIN(1./EME0)
  IF(ITE0.EQ.1) GO TO 175
  SLWC2=(TAN(THW-XMUW)+TAN(THE0-XMUE0))/2.
  YC2T=YW+SLWC2*(XC2-XW)
  FR9=YC2T-YC2T
  IF(ABS(FR9).LT.1.E-03) GO TO 175
  CALL ERROR(4,IT9,RAT,ER9,1.11,RAT1,ER91)
  GO TO 176
175 CONTINUE
  THV3=THI+DNUJV
  CALL PM(DNUV,PV3,TV3,EMV3,GV3,IV3,RHV3)
  THV1=THV3
  CALL FIX(XC,YC,THC,XMUC,XV1,YV1,THV1,0.,XV3,YV3,THV3,XMUV3,EMV3,
  1GV3,
  1PV3,TV3,RHV3,UV3,DNUV)
  AV=YV3 $ BV=TAN(THV3)
  CV=(YV2-AV-BV*(XV2-XV3))/(XV2-XV3)**2
  ZV3=GETZ(XV3)
  THV2=ATAN(BV+2.*CV*(XV2-XV3))
  IF(THV2.LT.0.) GO TO 462
  TAURV=THV2-THV3
  ITZ=1
  ITAU=0
  RAT=1.
545 CONTINUE
530 CONTINUE
  XZ=XC+RAT*(XD-XC)
  YZ=YC+RAT*(YD-YC)
  TAU=RAT*DNUC
  THZ=THC+RAT*(THD-THC)
  EMZ=EMC+RAT*(EMD-EMC)
  XMUZ=ASIN(1./EMZ)
  THY=THV3-TAU
  DNUY=DNUV+TAU
  CALL PM(DNUY,PY,TY,EMY,GY,UY,RHY)
  CALL FIX(XZ,YZ,THZ,XMUC+XV3,YV3,THV3+XMUV3,XY,YY,THY,XMUY,EMY,GY,
  1PY,TY,RHY,UY,DNUY)
  DNUE5=DNUV*2.*TAU+TAURV
  THE5=THV2
  CALL PM(DNUES,PE5,TE5,EME5,GE5,UE5,RHE5)

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```

ZE5=GETZ(XV2)
RQ3D=RHE5*UE5/ZE5
DNU35=DNUE5*SQRT(ZE5)
ITE5=1
220 CONTINUE
CALL PM(DNU35,PE5,TE5,EME5,GE5,UE5,RHE5)
RQ3T=RHE5*UES
ER05=(RQ3T-RQ3n)/RQ3D
IF(ABS(ER05).LT.1.E-03) GO TO 230
CALL FRROR(220,ITE5,DNU35,ER05,1,1,DNU351,ER051)
GO TO 220
230 CONTINUE
XMUE5=ASIN(1./EME5)
SL2T=(TAN(THY+XMUY)+TAN(THE5+XMUE5))/2.
YV2T=YY+SL2T*(XV2-XY)
IF(ITZ.EQ.1.AND.YV2T.GT.YV2) GO TO 542
FZ=YV2T-YV2
IF(ABS(FZ).LT.1.E-03) GO TO 540
IF(DNUC.EQ.0.) GO TO 540
CALL FRROR(5,ITZ,RAT,EZ1,1,RAT1,EZ1)
GO TO 530
542 ITAU=1
540 CONTINUE
DNUE2=DNUV+DNUC
CALL PM(DNUE2,PE2,TE2,EME2,GE2,UE2,RHE2)
THE2=THI+DNUV-DNUC
THE=THE2
RHF=RHE2 $ UF=UE2
CALL FIX(XC3,YC3,THC3,XMUC3,XD,YD,THD,XMUD,XF,YF,THF+XMUF+EMF+
1GF,
1PF,TF,RHF,UF,DNUE2)
SLE=(YV2-YC2)/(XV2-XC2)
THE=ATAN(SLE)
UFT=UF2 $ RHFT=RHF2
CALL FIX(XC3,YC3,THC3,XMUC3,XC2,YC2,THE,0.,XF,YF,THF+XMUF+EMF+
1GF,
1PF,TF,RHF,UF,DNUE2)
TF(XF,GT,XFT) GO TO 300
CALL FIX(XF,YF,THF+XMUF,XC2,YC2,THE,0.,XE2,YE2,THE2,XMUE2,EME2,
1GE2,
1PE2,TE2,RHE2,UE2,DNUE2)
ZF=GETZ(XF)
SLF=TAN(THF+XMUF)
CALL GEM(XF,YF,SLF,XC2,YC2,SLE,XE1,YE1)
ITE1=0
368 CONTINUE
RAT=(YE1-YC2)/(YE2-YC2)
DNUE1=DNUV+DNUC+(1.-RAT)*TAUC
CALL PM(DNUE1,PE1,TE1,EME1,GE1,UE1,RHE1)
THE1=THI+DNUV-DNUC-(1.-RAT)*TAUC
CALL FIX(XC2,YC2,THE,0.,XF,YF,THF+XMUF+XE1+YE1,THE1,XMUE1+EME1,
1GE1,
1PE1,TE1,RHE1,UE1,DNUE1)
TF(ITF1,FQ,1) GO TO 369
ITE1=1
GO TO 368

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```

369 CONTINUE
  GO TO 310
300 CONTINUE
  CALL FIX(XC2, YC2, THE, 0., XD, YD, THD, XMUD, XE2, YE2, THE2, XMUE2, EME2,
  1GE2,
  1PE2, TE2, RHE2, UE2, DNUE2)
  SLE2=TAN(THC3+XMUC3)
  CALL GEM(XC3, YC3, SLE, XC2, YC2, SLE, XE1, YE1)
  ITF1=0
381 CONTINUE
  RAT=(YE1-YC2)/(YE2-YC2)
  DNUE1=DNUC+TAUC+RAT*(DNUV-TAUC)
  CALL PM(DNUE1, PE1, TE1, EME1, GE1, UE1, RHE1)
  THE1=THI      +DNUC+TAUC+RAT*(DNUV-TAUC)
  CALL FIX(XC3, YC3, THC3, XMUC3, XC2, YC2, THE, 0., XE1, YE1, THE1, XMUE1, EME1
  1, GE1,
  1PE1, TE1, RHE1, UE1, DNUE1)
  IF(ITF1.EQ.1) GO TO 380
  ITF1=1
  GO TO 381
380 CONTINUE
310 CONTINUE
  THE3=THE2
  DNUE3=DNUE2
  CALL PM(DNUE3, PE3, TE3, EME3, GE3, UE3, RHE3)
  XMUE3=ASIN(1./EME3)
  IF(ITAU.NE.1) GO TO 311
  XG=XY $ YG=YY $ THG=THY $ RHG=RHY $ UG=UY $ EMG=EMY $ XMUG=XMUY
  PG=PY $ TG=TY
  XGT=XG
  GO TO 3588
311 CONTINUE
  THG=THE3
  RHG=RHE3 $ UG=UE3
  CALL FIX(XD, YD, THD, XMUD, XV3, YV3, THV3, XMUV3, XG, YG, THG, XMUG, EMG,
  1GG,
  1PG, TG, RHG, UG, DNUE3)
  RHGT=RHE3 $ UGT=UE3
  CALL FIX(XC2, YC2, THE, 0., XV3, YV3, THV3, XMUV3, XGT, YGT, THG, XMUG, EMG,
  1GGT,
  1PGT, TGT, RHGT, UGT, DNUE3)
  IF(XG.GT.XGT) GO TO 350
3588 CONTINUE
  CALL FIX(XC2, YC2, THE, 0., XG, YG, THG, XMUG, XE3, YE3, THE3, XMUE3, EME3,
  1GE3,
  1PE3, TE3, RHE3, UE3, DNUE3)
  ZG=GETZ(XG)
  IF(YE3.LE.YE2) GO TO 359
  SLE4=TAN(THG+XMUG)
  CALL GEM(XG, YG, SLE4, XC2, YC2, SLE, XE4, YE4)
  TT4=0
358 CONTINUE
  RAT=(YE4-YV2)/(YE3-YV2)
  DNUE4=DNUV+DNUC+(1.-RAT)*(TAURV+TAU)
  CALL PM(DNUE4, PE4, TE4, EME4, GE4, UE4, RHE4)
  THE4=THI      +DNUV+DNUC+(1.-RAT)*(TAURV+TAU)

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```

CALL FIX(XG,YG,THG,XMUG,XC2,YC2,THE,0.,XE4,YE4,THE4,XMUE4,EME4,
1GE4,
1PE4,TE4,RHE4,UE4,DNUE4)
IF(IT4.EQ.1) GO TO 359
IT4=1
GO TO 358
359 CONTINUE
IF(ITAU.EQ.0) GO TO 360
SLV32=(YV2-YV3)/(XV2-XV3)
SLG=TAN(THG+XMUG)
CALL GEM(XV3,YV3,SLV32,XG,YG,SLG,XV4,YV4)
ITV4=1
362 YV4=AV+RV*(XV4-XV3)+CV*(XV4-XV3)**2
THV4=ATAN(BV+2.*CV*(XV4-XV3))
TAURV4=THV4-THV3
DNUV4=DNUV+2.*TAU+TAURV4
CALL PM(DNUV4,PV4,TV4,EMV4,GV4,UV4,RHV4)
CALL FIX(XV4,YV4,7854,0.,XV4,YV4,0.,0.,XV4,YV4,THV4,XMUV4,EMV4,
1GV4,PV4,TV4,RHV4,UV4,DNUV4)
YV4T=YG+.5*(TAN(THG+XMUG)+TAN(THV4+XMUV4))*(XV4-XG)
ERV4=(YV4T-YV4)/YV2
IF(ARS(ERV4).LT.1.E-03) GO TO 361
CALL ERROR(361,ITV4,XV4,ERV4,1.1,XV41,ERV41)
ZV4=GETZ(XV4)
IF(ITV4.EQ.1) GO TO 361
GO TO 362
361 DNUE4=DNUV4
IF(YE3.LE.YE2) GO TO 460
CALL PM(DNUE4,PE4,TE4,EME4,GE4,UE4,RHE4)
THE4=THV4
CALL FIX(XC2,YC2,THE,0.,XV4,YV4,THV4,XMUV4,XE4,YE4,THE4,XMUE4,
1FME4,GE4,
1PE4,TE4,RHE4,UE4,DNUE4)
GO TO 360
350 CONTINUE
IT4=0
CALL FIX(XD,YD,THD,XMUD,XC2,YC2,THE,0.,XE3,YE3,THE3,XMUE3,EME3,
1GE3,
1PE3,TE3,RHE3,UE3,DNUE3)
IF(YE3.LE.YE2) GO TO 460
SLE4=TAN(THV3+XMUV3)
CALL GEM(XV3,YV3,SLE4,XC2,YC2,LE,XE4,YE4)
371 CONTINUE
RAT=(YE4-YV2)/(YE3-YV2)
DNUE4=DNUV+TAU+RAT*(DNUC-TAU)
CALL PM(DNUE4,PE4,TE4,EME4,GE4,UE4,RHF4)
THE4=THI+DNUV-TAU-RAT*(DNUC-TAU)
CALL FIX(XC2,YC2,THE,0.,XV3,YV3,THV3,XMUV3,XE4,YE4,THE4,XMUE4,EME4
1,GE4,
1PE4,TE4,RHE4,UE4,DNUE4)
IF(IT4.EQ.1) GO TO 370
IT4=1
GO TO 371
370 CONTINUE
360 CONTINUE
IF(YE3.LE.YE2) GO TO 460

```

```

X2(1)=XC2 $ X2(2)=XE1 $ X2(3)=YE2 $ X2(4)=XF3 $ X2(5)=XE4
X2(6)=XV2
Y2(1)=YC2 $ Y2(2)=YE1 $ Y2(3)=YE2 $ Y2(4)=YE3 $ Y2(5)=YE4
Y2(6)=YV2 $ EM2(1)=EME0 $ EM2(2)=EME1 $ EM2(3)=EME2 $ EM2(4)=EME3
EM2(5)=EME4 $ EM2(6)=EME5 $ TH2(1)=THE0 $ TH2(2)=THE1
TH2(3)=THE2 $ TH2(4)=THE3 $ TH2(5)=THE4 $ TH2(6)=THE5
DNUE(1)=DNUE0 $ DNUE(2)=DNUE1 $ DNUE(3)=DNUE2 $ DNUE(4)=DNUE3
DNUE(5)=DNUE4 $ DNUE(6)=DNUE5
RH2(1)=RHE0 $ RH2(2)=RHE1 $ RH2(3)=RHE2 $ RH2(4)=RHE3
RH2(5)=RHE4 $ RH2(6)=RHE5
U2(1)=UE0 $ U2(2)=UE1 $ U2(3)=UE2 $ U2(4)=UE3 $ U2(5)=UE4
U2(6)=UES
G2(1)=GE0 $ G2(2)=GE1 $ G2(3)=GE2 $ G2(4)=GE3 $ G2(5)=GE4
G2(6)=GE5
P2(1)=PE0 $ P2(2)=PE1 $ P2(3)=PE2 $ P2(4)=PE3 $ P2(5)=PE4
P2(6)=PE5
T2(1)=TE0 $ T2(2)=TE1 $ T2(3)=TE2 $ T2(4)=TE3 $ T2(5)=TE4
T2(6)=TE5
INDEX=0
180 CONTINUE
DO 160 I=1,6
Z2(I)=AZ*X2(I)**2+BZ*X2(I)+CZ
160 CONTINUE
THS1=i.5707963
IF(XV1.NE.XC1) THS1=ATAN((YV1-YC1)/(XV1-XC1))
THS2=ATAN((YV2-YC2)/(XV2-XC2))
ZIQ=.5*(GETZ(XC1)+GETZ(XV1))
XMASS1=RHI*UI*SIN(THS1-THI)/SIN(THS1)*ZIQ*(YV1-YC1)
THX1=(RHI*UI*UI*SIN(THS1-THI)*COS(THI)*(PI-PINF)*SIN(THS1))+ZIQ*(YV1-YC1)/SIN(THS1)
CALL XTH(X2,Y2,TH2,DNUE,PINF,THS2,THX1,XMASS1,THX)
ISH=0
GO TO 461
460 CONTINUE
ISH=1
WRITE(6,991)
991 FORMAT(# YE3.LE.YE2#)
461 CONTINUE
WRITE(6,1004) XC2,DNUV,DNUC,TAU, TAUC,TAURV,TAURC
1004 FORMAT( 32X*XC2  =#E12.4/32X*DNUV  =#E12.4/32X*DNUC  =#E12.4/
132X*TAU  =#E12.4/ 32X*TAUC  =#E12.4/32X*TAURV =#E12.4/32X*TAURC =
1#E12.4///)
WRITE(6,1007)
WRITE(6,1010) HOL(1),XV1,YV1,ZV1,THV1,FMV1,DNUV,PV1,TV1,HOL(2),XC1,
YC1,ZC1,THC1,EMC1,DNUC,PC1,TC1,HOL(3),XA,YA,ZA,THA,EMA,DNUA,PA,TA
1,HOL(4),XB,YB,ZB,
1THB,EMB,DNUC,PR,TB,HOL(5),XC,YC,ZC,THC,EMC,DNUV,PC,TC,HOL(6),XD,YD
1,ZD,THD,EMD,
1DNUD,PD,TD,HOL(7),XV3,YV3,ZV3,THV3,EMV3,DNUV,PV3,TV3,HOL(8),XC3,YC
13,ZC3,THC3,
1EMC3,DNUC,PC3,TC3
IF(XF.GT.XFT) WRITE(6,1005,
1005 FORMAT(20X*NO F POINT#)
IF(XF.LE.XFT) WRITE(6,1010) HOL(9),XF,YF,ZF,THF,EMF,DNUD,PF,TF
IF(XG.GT.XGT) WRITE(6,1006,
1006 FORMAT(20X*NO G POINT#)

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IF(XG.LE.XGT) WRITE(6,1010)HOL(10),XG,YG,ZG,THG,EMG,DNUD,PG,TG
IF(ITAU.EQ.1)WRITE(6,1010)HOL(11),XV4,YV4,ZV4,THV4,EMV4,DNUV4,PV4
1.TV4
  WRITE(6,1013)
1013 FORMAT(///)
  IF(ISH.EQ.1) GO TO 7384
  WRITE(6,1007)
1007 FORMAT(1X*PT.*6X*X*11X*Y*11X*Z*8X*THETA#7X*MACH*8X*DNU2D*10X*P*11X
  1#T#/)
  WRITE(6,1010)(HOLE(I),X2(I),Y2(I),Z2(I),TH2(I),EM2(I),DNUE(I),
  1P2(I),T2(I),I=1,6)
1010 FORMAT(1XA2,8E12.4)
7384 CONTINUE
  XI=XV1
  CALL POLY(XV1,YV1,TH1,XV3,THV3,XV2,THV2,XC1,YC1,XC2,THC2,XI)
  CALL THRUST(XV1,YV1,EMV1,XV3,YV3,THV3,XV2,XV4,TAU,DNUV,XC1,YC1,
  1EMC1,xC3,YC3,XC2,YC2,TAUC,DNUC,ITAU,THC1,THV1,THX)
  WRITE(6,99)
  WRITE(6,99)
  GO TO 6000
462 CONTINUE
  WRITE(6,992)
992 FORMAT(*THV2.LT.0*)
450 CONTINUE
6000 CONTINUE
5000 CONTINUE
END
```

```

SUBROUTINE CHAP
COMMON/A/ P1,TH1,EM1,GI,TI,HI,PHI,UI
COMMON/B/XA,YA,XB,YB,XC,YC,XD,YD
1THA,THB,THC,THD,EMA,EMB,EMC,EMD,XMUA,XMUB,XMUC,XMUD
COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
COMMON/R/PA,PR,PC,PD,TA,TB,TC,TD,GA,GB,GC,GD,UA,UB,UC,UD,RHA,
1RHB,RHC,RHD
COMMON/D/ PHI
XMUI=ASIN(1./EM1)
THA=TH1 $ RHA=RHI $ UA=UI
DMUA=1.
CALL FIX(XC1,YC1,TH1,XMUI,XV1,YV1,THI,XMUI,
1XA,YA,THA,XMUA,EMA,GA,
1PA,TA,RHA,UA,DNUA)
THB=THA+DNUC
CALL PM(DNUC,PR,TB,EMB,GB,UB,RHB)
FMB1=FMB
XMUB1=ASIN(1./FMB1)
CALL FIX(XC1,YC1,THB,XMUB1,XA,YA,THA,XMUA,XB,YB,THB,XMUB,EMB,GB,
1PR,TB,RHB,UB,DNUC)
THC=TH1+DNUV
CALL PM(DNUV,PC,TC,EMC,GC,UC,RHC)
FMC1=FMC
XMUC1=ASIN(1./EMC1)
CALL FIX(XA,YA,THA,XMUA,XV1,YV1,THC,XMUC1,XC,YC,THC,XMUC,EMC,GC,
1PC,TC,RHC,UC,DNUV)
60 DNUD=DNUV+DNUC
CALL PM(DNUD,PD,TD,EMD,GO,UD,RHD)
THD=TH1+DNUV-DNUC
CALL FIX(XB,YB,THB,XMUB,XC,YC,THC,XMUC,XD,YD,THD,XMUD,EMD,GD,
1PD,TD,RHD,UD,DNUD)
RETURN
END

```

```

SUBROUTINE THRUST(XV1,YV1,EMV1,XV3,YV3,THV3,XV2,XV4,TAU,DNUV,
1XC1,YC1,EMC1,XC3,YC3,XC2,YC2,TAUC,DNUC,      ITAU,THC1,THV1,THX)
COMMON/D3/ AZ,RZ,CZ
COMMON /V/ AV,RV,CV
COMMON/P/ PINF
COMMON/SHF/ XSHF,YSHF
COMMON/POL/ IPR,IPOLY
COMMON/THRMAX/THRMAX
COMMON/PMPM/ PMOM
100 FORMAT(8E13.5)
GETZ(X5)=AZ*X5+X5+BZ*X5+CZ
XLTF=0.
XTH=0.
XMOM=0.
DX=(XV2-XV1)/50.
N=(XV3-XV1)/DX+1.
DXN=(XV3-XV1)/FLOAT(N)
N=N+1
CALL PM(DNUV,PA,TA,EMA,GA,UA,RHA)
XA=XV1 $ YA=YV1 $ ZA=GETZ(XA)
THA=THV1
CALL FIX(XA,YA,7854+0.,XA,YA,0.,0.,XA,YA,THA,XMUA,EMA,GA,PA,TA,
1RHA+UA,DNUV)
PA=PA_PINF
PX=PA+PINF
PX=PX_PINF
IF(IPR.EQ.1) GO TO 50
WRITE(6,110)
110 FORMAT(//35X*VEHICLE UNDERSURFACE*/7X*X*12X*Y*12X*Z*9X*P/PINF*
1RX*MACH*9X*LIFT*RX*THRUST*7X*MOMENT*)
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
50 CONTINUE
DO 10 I=2,N
XA=XA+DXN
YA=YV1+(XA-XV1)/(XV3-XV1)*(YV3-YV1)
ZB=GETZ(XB)
THR=ATAN((YV3-YV1)/(XV3-XV1))
CALL PM(DNUV,PA,TB,EMB,GB,UB,RHB)
CALL FIX(XB,YB,7854+0.,XB,YB,0.,0.,XB,YB,THB,XMUB,EMB,GB,PR,TB,
1RHB+UR,DNUV)
PR=PA_PINF
DUM=(PA+PB)*(ZB+ZA)/4.
DXLF=DUM*(XB-XA)
DXTH=DUM*ABS(YB-YA)
YBB=(YA+YB)/2.-YSHF
XBB=(XA+XB)/2.-XSHF
DXMOM=-YBB*DXTH+XBB*DXLF
XLIF=XLTF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PR
EMA=EMB
PX=PA+PINF
PX=PX_PINF
IF(IPR.EQ.1) GO TO 51
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM

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51 CONTINUE
10 CONTINUE
N=(XV2-XV3)/DX+1.
DXN=(XV2-XV3)/FLOAT(N)
N=N+1
DO 20 I=2,N
XB=XA+DXN
YB=AV+BV*(XB-XV3)+CV*(XB-XV3)*#2
ZB=GETZ(XB)
THB=ATAN(BV+2.*CV*(XB-XV3))
TAURB=THB-THV3
RATB=(XB-XV3)/(XV2-XV3)
IF (ITAU, EQ, 1) RATB=(XB-XV3)/(XV4-XV3)
IF (RATB, GT, 1.) RATB=1.
DNUB=DNUV+TAURB*2.*RATB*TAU
X1=XV3 $ X2=XV2
IF (ITAU, EQ, 1) X2=XV4
RATA=((X1-XC1)/(XB-XC1)-1.)/((X1-XC1)/(X2-XC1)-1.)
IF (RATA, GE, 1.) RATA=1.
TAUX=ATAN(RATA+TAN(TAU))
DNUB=DNUV+TAURB*2.*TAUX
CALL PM(DNUB, PR, TB, EMB, GB, UB, RHB)
CALL FIX(XB, YB, +7854.0, XB, YB, 0., XB, YB, THB, XMUB, EMB, GB, PB, TB,
1RHB, UR, DNUB)
PB=PR+PINF
DUM=(PA+PB)*(ZB-ZA)/4.
DXLF=DUM*(XB-XA)
DXTH=0.5*ABS(YB-YA)
YBB=(YA+YB)/2.-YSHF
XBB=(XA+XB)/2.-XSHF
DXMOM=YBB*DXTH+XBB*DXLF
XLIF=xLIF+DXLF
XTH=XTH+DXTH
XMOM=xMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PB
EMA=EMB
PX=PA+PINF
PX=PX/PINF
IF (IPR, EQ, 1) GO TO 52
WRITE(6,100) XA, YA, ZA, PX, EMA, XLIF, XTH, XMOM
52 CONTINUE
20 CONTINUE
XLV=XLIF
XTHV=XTH
XMOMV=XMOM
WRITE(6,101)
101 FORMAT(/)
XA=XC1 $ YA=YC1 $ ZA=GETZ(XA)
XLIF=0.
XTH=0.
XMOM=0.
N=(XC2-XC1)/DX+1.
DXN=(XC3-XC1)/FLOAT(N)
N=N+1
CALL PM(DNUC, PA, TA, EMA, GA, UA, RHA)
THA=THC1

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```

CALL FIX(XA,YA,.7854,0.,XA,YA,0.,0.,XA,YA,THA,XMUA,EMA,GA,PA,TA,
1RHA,UA,DNUC)
PA=PA-PTNF
PX=PA+PINF
PX=PX/PINF
IF (IPR.EQ.1) GO TO 53
WRITE(6,111)
111 FORMAT(//50X*COOL* /7X*X#12X*Y#12X*Z#9X*P/PINF*
18X*MACH#9X*LIFT#RX*THRUST#7X*MOMENT#)
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
53 CONTINUE
DO 30 I=2,N
XB=XA+DXN
YB=YC1+(XB-XC1)/(XC3-XC1)*(YC3-YC1)
ZB=GETZ(XB)
THB=ATAN((YC3-YC1)/(XC3-XC1))
CALL PM(DNUC,PR,TB,EMB,GB,UB,RHB)
CALL FIX(XB,YB,.7854,0.,XB,YB,0.,0.,XB,YB,THB,XMUB,EMB,GB,PB,TB,
1RHB,UB,DNUC)
PB=PB-PINF
DUM=(PA+PB)*(ZB+ZA)/4.
DXLF=-DUM*(XB-XA)
DXTH=DUM*ABS(YB-YA)
YBB=(YA+YB)/2.-YSHF
XBB=(XA+XB)/2.-XSHF
DXMOM=-YBB*DXTH+XBB*DXLF
XLIF=XLIF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PB
EMA=EMB
PX=PA+PINF
PX=PX/PINF
IF (IPR.EQ.1) GO TO 54
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
54 CONTINUE
30 CONTINUE
N=(XC2-XC3)/DX+1.
IF (XC2.EQ.XC3) GO TO 60
DXN=(XC2-XC3)/FLOAT(N)
N=N+1
DO 40 I=2,N
XB=XA+DXN
YB=YC3+(XB-XC3)/(XC2-XC3)*(YC2-YC3)
ZB=GETZ(XB)
RAT=(XB-XC3)/(XC2-XC3)
DNUB=DNUC+RAT*2.*TAUC
RATA=((XC3-XV1)/(XB-XV1)-1.)/((XC3-XV1)/(XC2-XV1)-1.)
TAUY=ATAN(RATA*TAN(TAUC))
DNUB=DNUC+2.*TAUY
CALL PM(DNUB,PR,TB,EMB,GB,UB,RHB)
THR=ATAN((YC2-YC3)/(XC2-XC3))
CALL FIX(XB,YB,.7854,0.,XB,YB,0.,0.,XB,YB,THB,XMUB,EMB,GB,PB,TB,
1RHB,UB,DNUB)
PB=PB-PINF
DUM=(PA+PB)*(ZB+ZA)/4.

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DXLF=-DIJM*(XB-XA)
DXTH=JUM*ABS(YR-YA)
YBB=(YA+YB)/2.-YSHF
XBB=-((XA+XB)/2.-XSHF)
DXMOM=YBB*DXTH+XBB*DXLF
XLIF=XLIF+DXLF
XTH=XTH+DXTH
XMOM=XMOM+DXMOM
XA=XB $ YA=YB $ ZA=ZB $ PA=PR
EMA=EMB
PX=PA+PTNF
PX=PX/PINF
IF(IPR.EQ.1) GO TO 55
WRITE(6,100) XA,YA,ZA,PX,EMA,XLIF,XTH,XMOM
55 CONTINUE
40 CONTINUE
60 CONTINUE
XTH=XTH+XTHV
XLIF=XLIF+XLV
XMOM=XMOM+XMOMV
WRITE(6,4203) XLIF
4203 FORMAT(//20X*TOTAL LIFT =#E12.4)
WRITE(6,1008) XTH
1008 FORMAT(/20X*THRUST (FROM COWL AND VEHICLE UNDERSURFACE) =#E12.4)
WRITE(6,4206) XMOM
4206 FORMAT(/20X*MOMENT (FROM COWL AND VEHICLE UNDERSURFACE) =#E12.4)
IF(THX.LT.1.E+09) GO TO 4201
WRITE(6,4200)
4200 FORMAT(/20X*EXIT PROFILE AND THRUST AND MOMENT (FROM SIDE WALLS) NOT CALCULATED.=)
GO TO 4212
4201 IF(THX.GT.0.) GO TO 4205
WRITE(6,4204) THX
4204 FORMAT(/20X*THRUST (FROM SIDE WALLS) =#E12.4)
PMOM1=0.
WRITE(6,4211) PMOM1
4211 FORMAT(/20X*MOMENT (FROM SIDE WALLS) =#E12.4)
GO TO 4212
4205 DTHQ=THX-XTH
WRITE(6,4204) DTHQ
XTH=THX
PMOM1=PMOM=XMOM
WRITE(6,4211) PMOM1
4212 CONTINUE
PTHL=(THRMAX-XTH)/THRMAX*100.
WRITE(6,1563) PTHL
1563 FORMAT(/40X*PERCENT THRUST LOSS =#F6.3)
RETURN
END

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```

SUBROUTINE XTH(X2,Y2,TH2,DNUE,PINF,THS2,
1THX1, XMASS1,THX)
COMMON/D3/AZ,BZ,CZ
COMMON/SHF/XSHF,YSHF
COMMON/PMPM/ PMOM
COMMON/DNU3D/DNU3D
DIMENSION XNU(50),X(50),Y(50),Z(50),EM(50),P(50),TH(50),T(50)
DIMENSION DNUE(10),X2(10),Y2(10),TH2(10),RHO(50),U(50),G(50)
GETZ(X5)=AZ*X5+BZ*X5+CZ
THX=0.
IF(AZ+BZ.EQ.0.) RETURN
INDEX=0
DO 10 I=1,5
J1=(I-1)*5+1
J2=I*5
IF(I.EQ.5) J2=26
DO 20 J=J1,J2
RAT=FLOAT(J-J1)/FLOAT(J2-J1)
XNU(J)=DNUE(I)+RAT*(DNUE(I+1)-DNUE(I))
X(J)=Y2(I)+RAT*(Y2(I+1)-Y2(I))
Y(J)=Y2(I)+RAT*(Y2(I+1)-Y2(I))
TH(J)=TH2(I)+RAT*(TH2(I+1)-TH2(I))
CALL PM(XNU(J),P(J),T(J),EM(J),G(J),U(J),RHO(J))
CALL FIX(X(J),Y(J),.7854,0.,X(J),Y(J),0.,0.,X(J),Y(J),TH(J),XNU,
1EM(J),G(J),P(J),T(J),RHO(J),U(J),XNU(J))
XNU(J)=DNU3D
Z(J)=GETZ(X(J))
20 CONTINUE
10 CONTINUE
86 CONTINUE
I=1
F1=RHO(I)*U(I)*SIN(THS2-TH(I))/SIN(THS2)*Z(I)
F1=(RHO(I)*U(I)*U(I)*SIN(THS2-TH(I))*COS(TH(I))+(P(I)-PINF)*SIN(TH
1S2))*Z(I)/SIN(THS2)
W1=(RHO(I)*U(I)*U(I)*SIN(THS2-TH(I))*SIN(TH(I))+(P(I)-PINF)*COS(TH
1S2))*Z(I)/SIN(THS2)
XMASS2=0.
THX2=0.
PMOM=0.
DO 150 I=2,26
F2=RHO(I)*U(I)*SIN(THS2-TH(I))/SIN(THS2)*Z(I)
F2=(RHO(I)*U(I)*U(I)*SIN(THS2-TH(I))*COS(TH(I))+(P(I)-PINF)*SIN(TH
1S2))*Z(I)/SIN(THS2)
W2=(RHO(I)*U(I)*U(I)*SIN(THS2-TH(I))*SIN(TH(I))+(P(I)-PINF)*COS(TH
1S2))*Z(I)/SIN(THS2)
THX2=THX2+.5*(F1+F2)*(Y(I)-Y(I-1))
XMASS2=XMASS2+.5*(E1+E2)*(Y(I)-Y(I-1))
DUM1=.5*(F1*(Y(I-1)-YSHF)+F2*(Y(I)-YSHF))
DUM2=.5*(W1*(X(I-1)-XSHF)+W2*(X(I)-XSHF))
PMOM=PMOM+(DUM1+DUM2)*(Y(I)-Y(I-1))
F1=F2 $ F1=F2 $ W1=W2
150 CONTINUE
RATM=XMASS2/XMASS1
FMS=RATM-1
IF(ABS(FMS).LT.1.E-03) GO TO 4625
INDEX=INDEX+1

```

```
IF(INDEX.GT.1)GO TO 4625
DO 170 I=1,26
  FM1=FM(EM(I),G(I))
  FM2=FM1/RATM
  ITM=1
  EMT=RATM*EM(I)
197 CONTINUE
  FMT=FM(EMT+G(I))
  FRM=(FM2-FMT)/FM2
  IF(ABS(ERM).LT.1.E-03)GO TO 171
  DUMD=1./RATM
  CALL ERROR(6,ITM,EMT,ERM,DUMD,FMT1,ERM1)
  GO TO 197
171 CONTINUE
  DUM=SQRT((G(I)+1.)/(G(I)-1.))
  ETSQ=SQRT(EMT*EMT-1.)
  ESQ=SQRT(EM(I)*EM(I)-1.)
  XNU2=DUM*ATAN(ETSQ/DUM)-ATAN(ETSQ)
  XNU1=DUM*ATAN(ESQ/DUM)-ATAN(ESQ)
  XNU(J)=XNU(I)+XNU2-XNU1
  CALL PM(XNU(I),P(I)+T(I),EM(I),G(I),U(I),RHO(I))
170 CONTINUE
  GO TO 86
4625 CONTINUE
  THX=THX2/RATM-THX1
  RETURN
  END
```

```
SUBROUTINE FIX(X1,Y1,TH1,XMU1,Y2,Y2,TH2,XMU2,X3,Y3,TH3,XMU3,EM3,G3
1,P3,T3,RH3,U3,DNU3)
COMMON/D3/ AZ,BZ,CZ
COMMON/DNU3D/DNU3D
ITM=0
99 CONTINUE
SL1=TAN(TH1+XMU1)
SL2=TAN(TH2-XMU2)
CALL GEM(X1,Y1,SL1,X2,Y2,SL2,X3,Y3)
IF(X3.LT.0.) WRITE(6,100)
100 FORMAT(* NO X3 POINT IN FIX*)
IF(X3.LT.0.) STOP
RQ2D=RH3*U3
200 CONTINUE
IF(X3.LT.0.) GO TO 99
Z=AZ*X3+BZ*X3+CZ
RQ3D=RQ2D/Z
DNU3D=DNU3
ITQ=1
FRT=.001
10 CONTINUE
CALL PM(DNU3D,P3,T3,EM3,G3,U3,PH3)
RQ3T=RH3*U3
ERQ=(RQ3T-RQ3D)/RQ3D
IF(ITQ.GE.10) FRT=.005
IF(ABS(ERQ).LT.ERT) GO TO 20
CALL ERROR(20,ITQ,DNU3D,ERQ,1,1,DNU3D1,ERQ1)
GO TO 10
20 CONTINUE
XMU3=ASIN(1./EM3)
SL13=SL1/2.+.5*TAN(TH3+XMU3)
IF(XMU1.EQ.0.) SL13=SL1
SL23=SL2/2.+.5*TAN(TH3-XMU3)
IF(XMU2.EQ.0.) SL23=SL2
CALL GEM(X1,Y1,SL13,X2,Y2,SL23,X3,Y3)
IF(ITM.EQ.1) GO TO 300
ITM=1
GO TO 200
300 CONTINUE
RETURN
END
```

```
SUBROUTINE THM(RHI,UI,PI,PINF,YV1,YC1,DYV,XV2,THRMAX,DNUV,DNUC,XC2
1)
COMMON/D3/AZ,BZ,CZ
A1=YV1-YC1
F1=RHI*UI*A1
Z2=AZ*XV2*XV2+BZ*XV2*CZ
Z5=AZ*XC2*XC2+BZ*XC2*CZ
A2=(Z2+Z5)/2.*DYV
IT=1
DNU=(DNUV+DNUC)*SQR((Z2+Z5)/2.)
10 CALL PM(DNU,P2,T2,EM2,G2,U2,RH2)
F2=RH2*U2*A2
ERT=(F2-F1)/F1
IF(ABS(ERT).LT.1.E-04) GO TO 20
CALL ERROR(99,IT,DNU,ERT,9,DNU1,ERT1)
GO TO 10
20 TH1=(PI-PINF+RHI*UI*UI)*A1
TH2=(P2-PINF+RH2*U2*U2)*A2
THRMAX=TH2-TH1
      -
```

RETURN  
END

```
FUNCTION FM(XM,G)
FM=X^M/(1.+(G-1.)/2.*X^M*2.)**((G+1.)/2.)/(G-1.))
RETURN FM
END
```

```
SUBROUTINE GEM(XA,YA,SLA,XB,YB,SLB,XC,YC)
XC=(YA-SLA*XA-SLB*XB)/(SLA-SLB)
YC=YA+SLA*(XC-YA)
RETURN
END
```

```
SUBROUTINE ERROR (I,IT,X,ER,F,X1,ER1)
IT=IT+1
IF(IT.LT.15) GO TO 12
WRITE(6,13)
13 FORMAT(*ERROR TEST NUMBER *)  
      WRITE(6,20) I
20 FORMAT(I5)
STOP
12 IF(IT.GT.2) GO TO 14
ER1=ER
X1=X
Y=X#F
IF(X.EQ.X1) X=X+.#2
RETURN
14 X0=X1-ER1*(X-X1)/(ER-ER1)
ER1=ER
X1=X
Y=X0
RETURN
END
```

```

SUBROUTINE POLY(XV1,YV1,TH1,XV3,THV3,XV2,THV2,
1XC1,YC1,XC2,THC2,X1)
COMMON/X/A11,A12,A13,A21,A22,A23,A31,A32,A33
COMMON/POL/ 1PR,TPOLY
DIMENSION X(10),Y(10),TH(10)
IF(IPOLY.EQ.1) GO TO 20
IT=0
X(1)=XV1
X(2)=XV1+.01*(XV2-XV1)
X(3)=XV3
X(4)=XV2
TH(1)=TH1
TH(2)=THV3
TH(3)=THV3
TH(4)=THV2
TH(1)=-TH(1) $ TH(2)=-TH(2) $ TH(3)=-TH(3) $ TH(4)=-TH(4)
Y(1)=YC1
N=3
WRITE(6,100)
100 FORMAT(1//30X*VEHICLE COORDINATES*/
115X*X*4X*T0*4X*X*15X*COORDINATES*)
30 DO 10 I=1,N
Y2=X(I+1)-X1
Y1=X(I)-X1
A=(TAN(TH(I+1))-TAN(TH(I)))/2./*(X2-X1)
B=TAN(TH(I+1))-2.*A*X2
C=Y(I)-B*X1-A*X1*X1
Y(I+1)=A*X2+C*X2+0*X2+C
WRITE(6,69) X(I),X(I+1),A,B,C
69 FORMAT(10X5E11.3)
10 CONTINUE
IF(IT.EQ.1)GO TO 20
IT=1
X(1)=YC1$X(2)=X(1)+.01*(XV2-XV1)
Y(3)=YC2
TH(2)=THC2
TH(3)=TH(2)
TH(2)=-TH(2) $ TH(3)=-TH(3)
Y(1)=YV1
N=2
WRITE(6,101)
101 FORMAT(1/30X*COWL COORDINATES*/
115X*X*4X*T0*4X*X*15X*COORDINATES*)
GO TO 30
20 CONTINUE
RETURN
END

```

```

SUBROUTINE PM(DNU,P2,T2,EM2,G2,U2,RH2)
COMMON/A/ P1,TH1,EM1,GI,FI,HI,CHI,UI
COMMON/D/ PHI1
DTH=2./57.3
IFAN=DNU/DTH
IF(DTH.GE.DNU)DTH=DNU
IF(DTH.EQ.DNU)IFAN=1
P1=P1
T1=TI
EM1=EM1
HI=HJ
GI=GI
RH1=RH1
A1=SORT(G1*P1/RH1)
U1=UT
M1=EM1*A1
U1=U1+U1
HT=H1+U1/2.
P1=A1*LOG(P1)
XNU1=0.
XNU1=0.
DO 10 I=1,IFAN
IF(I.EQ.1)DTH=DNU-XNU
XNU1=SIN(1./EM1)
R1=G1*EM1/COS(XNU1)
P2=-S1*DTH+P1
RH2=(P2-P1)/G1
RH2=RH1*EXP(RH2)
P2P=EXP(P2)
P1P=EXP(P1)
U2=U1-2.*G1/(G1-1.)*(P2P/RH2-P1P/RH1)
U2=HT-U2/d.
T2=HT(P2P,PHI1,H2)
GP=FGAM(T2,P2P,PHI1)
A2=02*P2P/RH2
GM2=SORT(U2/A2)
XNU=XNU1+DTH
XNU1=XNU
P1=P2
T1=T2
G1=G1
EM1=EM2
U1=U2
RH1=RH2
10 CONTINUE
P2=EXP(P2)
U2=SORT(U2)
RETURN
END

```

```

FUNCTION F1(P1,F,H5)
DATA I63/17
IFLAG=0
P=P1*1.0)325E+05/2116.
H=H5 /10.7639/1.E+06
F2=F*F
A10=ALOG(P1/2.3-5.
79=.125*A10*A10 - .275*A10
IT=1
IF(I63,EQ,1) GO TO 1000
I63=1
T=1500.
T0=1500.
IF(F,GE,0.) GO TO 120
T=600.
T0=T
1000 CONTINUE
IF(F,LT,0.) GO TO 400
GO TO 120
50 E0=(H_H1)/H
IF(ABS(E0)*LT.1.E-04) GO TO 34
500 T =T0+1.1
502 JT=2
IF(F,LT,0.) GO TO 400
GO TO 120
100 F1=(H_H1)/H
IF(ABS(E1)*LT.1.E-04) GO TO 34
IT=IT+1
IF(IT,LT,21) GO TO 10
IF(ABS(T-2000.)*LT.10.) GO TO 830
WRIT(0,631) P1,H5,T
831 FORMAT(* ERROR IN F1/* P1 = *E13.5,5*H1 = *E13.5,5*T = *E13.5
1)
STOP
830 IF(IFLAG,NE,1) GO TO 504
IFLAG=1
T0=2000.
T=2000.
IF(F,LT,0.) GO TO 400
GO TO 120
504 WRIT(0,11) E1
11 FORMAT(* TEMPERATURE IN FT SET TO 2000 - ERROR = *E13.5)
GO TO 34.
10 T9=T0-E0*(1-F1)/(E1-E0)
505 E0=E1
T0=T
T=T9
IF(F,LT,0.) GO TO 400
120 A=1.E-07*(-.1042*F2 + .8242*F + .987)
B=.001*(-.01167*F2 + .1503*F + .938)
C=-.0284*F2 + .6731*F + .4243
IF(F,LT,1.) GO TO 190
A=1.E-07*(1.787*F2 + 5.48*F + 5.4)
B=.001*(-.1067*F2 + 1.11*F + 1.0)
C=-.0333*F2 + 9.74*F - 2.818
190 TF(I,E,2000.) GO TO 290

```

```

A=.000001*(1.792*F2 + .3983*F+.31)
B=.001*(-9.05*F2 -.07917*F+.245)
C=10.80*F2 -.1183*F+.97
IF(F,.1,E.1.) GO TO 290
A=.000001*(4.81*F2 -13.9*F+11.59)
B=.001*(-23.08*F2 +66.82*F-52.61)
C=27.05*F2 -73.73*F+58.39
290 H1=A*T*T+B*T+C
IF(T.LE.2000.) GO TO 370
H1=H1*(1.+(1.+F)*(T/2000.-1.)*.79)
370 CONTINUE
GO TO 350
400 T2=T*T
T3=T2*1
T4=T3*T
T5=T4*T
IF(F,.1,T,-1.5) GO TO 450
XMM1=16.043
A1=4.2497678
A2=-6.9126562E-03
A3=3.1682134E-05
A4=-4.9715432E-08
A5=9.5103580E-12
A6=-1.0186632E+04
GO TO 460
450 CONTINUE
A1=1.1202436
A2=1.3945716E-02
A3=2.6568374E-16
A4=-1.1560272E-98
A5=5.2386969E-12
A6=5.3328886E+03
XMM1=28.154
460 H1=A1+A2*T2/2+A3*T3/3+A4*T4/4+A5*T5+A6
H1=H1*8314.7XMM1/1.E+06
350 IF(IT,E0,1) GO TO 50
GO TO 100
340 T0=T
FT=T*1.*C
RETURN
END

```

```

FUNCTION RHEQ(H,P1,F,T)
T1=FT(P1,F,H)
T=T1/1.8
P=P1*1.01325E+05/2116.
IF(F.LT.0.) GO TO 2260
FNM=1.53*F*F-5.895*F+28.965
FNN=1.6*F*F-10.6*F+33.6
IF(T.GT.2000.) GO TO 2030
XM=FNM
IF(F.GT.1.1*) GO TO 2160
XM=FNN
GO TO 2160
2030 FF=F*F
A=-2.3*FF+4.01*F+1.736
B=8.61*FF-15.42*F-6.66
C=-16.88*FF+33.21*F+14.58
XN=-.4375*FF+.4625*F+2.08
D=A*(ALOG(P)/2.3)*1.5+B*(ALOG(P)/2.3)*C
XM=FNN=D*((T-2000.)/1000.)*XN
IF(F.LT.1.) GO TO 2160
A=-.822*FF+2.363*F+1.905
B=2.76*FF-7.56*F-8.68
C=-3.6*FF+1.36*F+27.15
XN=-.47*FF+1.625*F+.35
D=A*(ALOG(P)/2.3)*1.5+B*(ALOG(P)/2.3)*C
XM=FNN=D*((T-2000.)/1000.)*XN
GO TO 2160
2260 KF=F-.5
IF(KF.EQ.-1) XM=16.043
IF(KF.EQ.-2) XM=28.054
2160 RHEQ=P*XM/T/8314.3*6.2428E-02/32.174
T=T*1.8
P=TURE
END

```

```
FUNCTION FGAM(T1,P1,F)
T=T1/1.8
T2=1#1
P=P1*1.01325E+95/2146.
XM=0.
IF(F.1 T.0.) GO TO 550
IF(T.LE.1000.) GO TO 440
XM=-2.15E-08*T2 +.000091*T-.0645
440 XN=4.F-09*T2 -.00002*T-.019
IF(F.LE.1.) GO TO 470
XN=.0339*SGRT(T)-.000391*T-.681
470 G=-1.833E-07*T2 +.000075*T+1.367
IF(T.LT.500.) GO TO 520
G=2.E-08*T2 -.000138*T+1.423
IF(T.LT.2000.) GO TO 520
G=7.267E-08*T2 -.000457*T+1.85
520 G=G+XM*(ALOG(P)/2.3-5.)+XN*(F-1.)
GO TO 530
550 T3=T2*T
T4=T3*T
CP=A1+A2*T+A3*T2+A4*T3+A5*T4
G=CP*(CP-1.)
530 CONTINUE
FGAM=G
RETURN
END
```

```

FUNCTION FM(P1,F,T1)
P=P1*1.0)325E+05/2116.
T=T1/1.0
F2=F*F
IF(F.L1.0.) GO TO 400
IF(T.GT.2000.) GO TO 190
IF(F.GT.1.) GO TO 191
120 A=1.E-07*(-.1042*F2 +.8242*F+.987)
B=.001*(.01167*F2 +.1503*F+.938)
C=-.0284*F2 +.6731*F+.4293
GO TO 200
191 A=1.E-07*(1.787*F2 -5.48*F+.4)
B=.001*(-.1867*F2 +1.11*F+.176)
C=-.0033*F2 +3.975*F-2.808
GO TO 200
190 IF(F.GT.1.) GO TO 192
A=.000001*(1.702*F2 +.3453*F+.31)
B=.001*(-9.05*F2 -.07917*F+.245)
C=10.86*F2 -.1183*F+.97
GO TO 200
192 A=.000001*(4.01*F2 -13.9*F+11.59)
B=.001*(-23.08*F2 +66.82*F-52.61)
C=27.05*F2 -73.73*F+58.39
290 H1=A*T*T+B*T+C
IF(T.LE.-2000.) GO TO 370
A10=A100(P)/2.0-5.
Z9=-.125*A10*A10 -.275*A10
H1=H1+(1.+F)*(T/2000.-1.)**2
370 H1=H1+1.E+06
GO TO 340
400 T2=T*T
T3=T*T
T4=T*T
T5=T*T
H1=A1+42*T2/2.+A3*T3/3.+A4*T4/4.+A5*T5+A6
W1=H1*A314./XMM1
340 CONTINUE
FH=H1+1.E.7639
RETURN
END

```